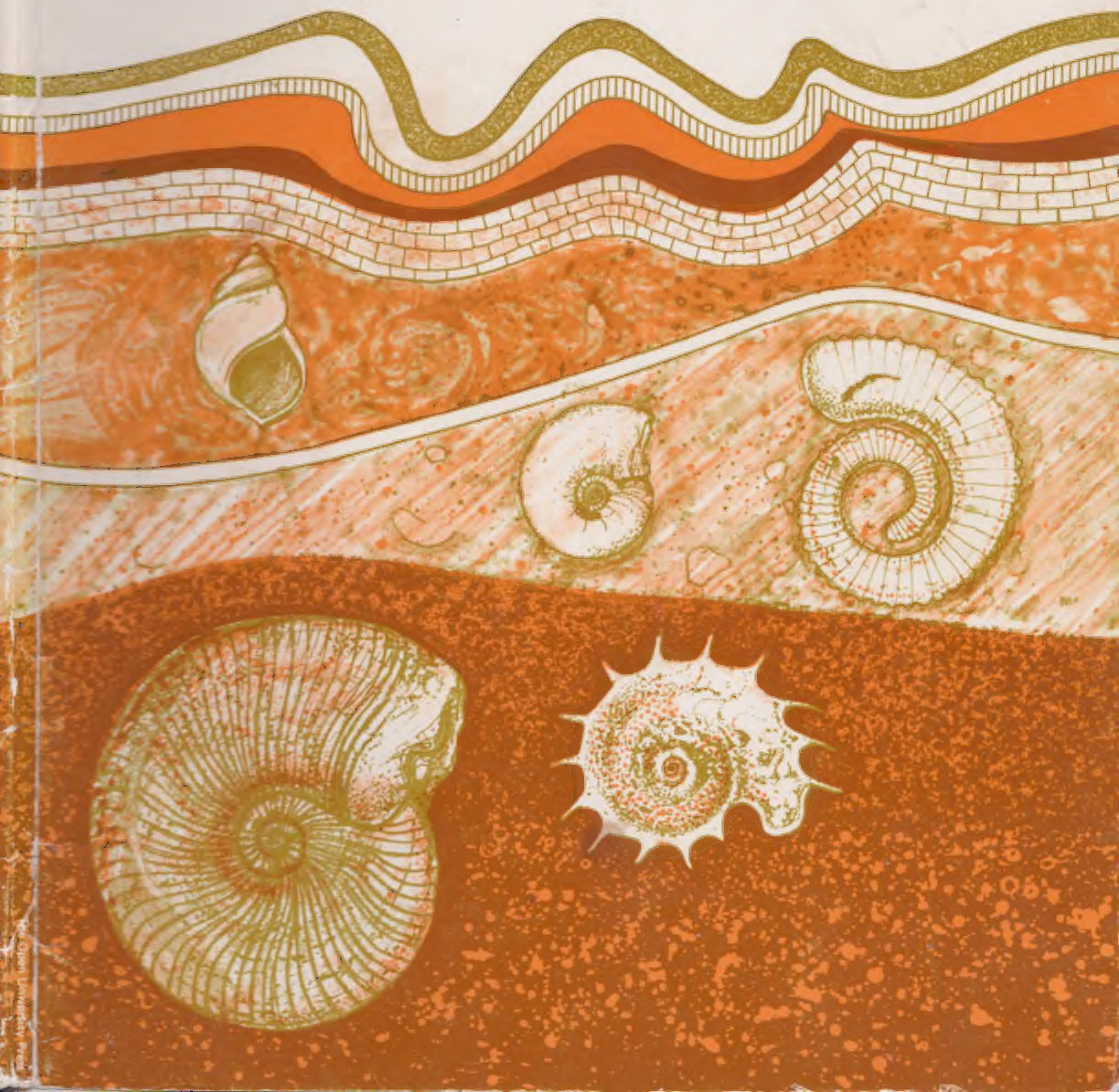
S 100 26 and 27

THE OPEN UNIVERSITY

Science Foundation Course Units 26 and 27

Earth History I and II



S 100 26 and 27 · Earth History I and II

The Open University

Science Foundation Course Unit 26

EARTH HISTORY : 1

Prepared by the Science Foundation Course Team

THE OPEN UNIVERSITY PRESS

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1.3

Contents

Introduction to Units 26 and 27

The main aim of these two Units is to give you some insight into the methods used to reconstruct events in the Earth's history. So far, we have devoted most of our attention to the structure and evolution of the Earth's crust. Now we examine the Earth's surface, what past environments must have been like and how life may have originated on it.

We do not expect much factual recall of the material in these Units. We hope you will enjoy reading them and, whilst doing so, will gain some insight into the methods by which Earth history has been and is being deciphered.

Objectives

When you have finished this Unit, you should be able to:

1 Define correctly in your own words, or recognize the best definitions of, or distinguish between true and false statements concerning terms, concepts or principles given in column 3 of Table A.

2 Recognize the basic assumption made in applying the principle of uniformitarianism.

3 List the data required in the study of a present-day sedimentary environment.

4 Select from these data (3) the evidence that would remain in the rocks for study by 'future' Earth scientists.

5 Given the relevant information, make simple deductions concerning the type of environment in which sediments were deposited, and the order of events during the geological history of a given area.

6 Correctly list, or recognize from given examples, the major sedimentary units of a delta, explain their properties in terms of the processes involved, and outline the characters of ancient deltaic sequence.

7 Correctly identify where orogenesis occurs in terms of plate tectonics.

8 Explain, in terms of plate tectonic processes, how the features of fold mountain chains (orogenic belts) are produced.

9 Recognize why older orogenic belts are considered to be 'fossil' plate margins.

10 Correctly define and distinguish between lithostratigraphy and biostratigraphy.

11 Given data on the radiometric age of igneous or metamorphic rocks, correctly assign age limits to the units of a sedimentary sequence.

12 Explain in your own words how the stratigraphic column has been erected by the amalgamation of radiometric, lithostratigraphic and biostratigraphic studies, and use evidence obtained from such studies to construct a 'time scale'.

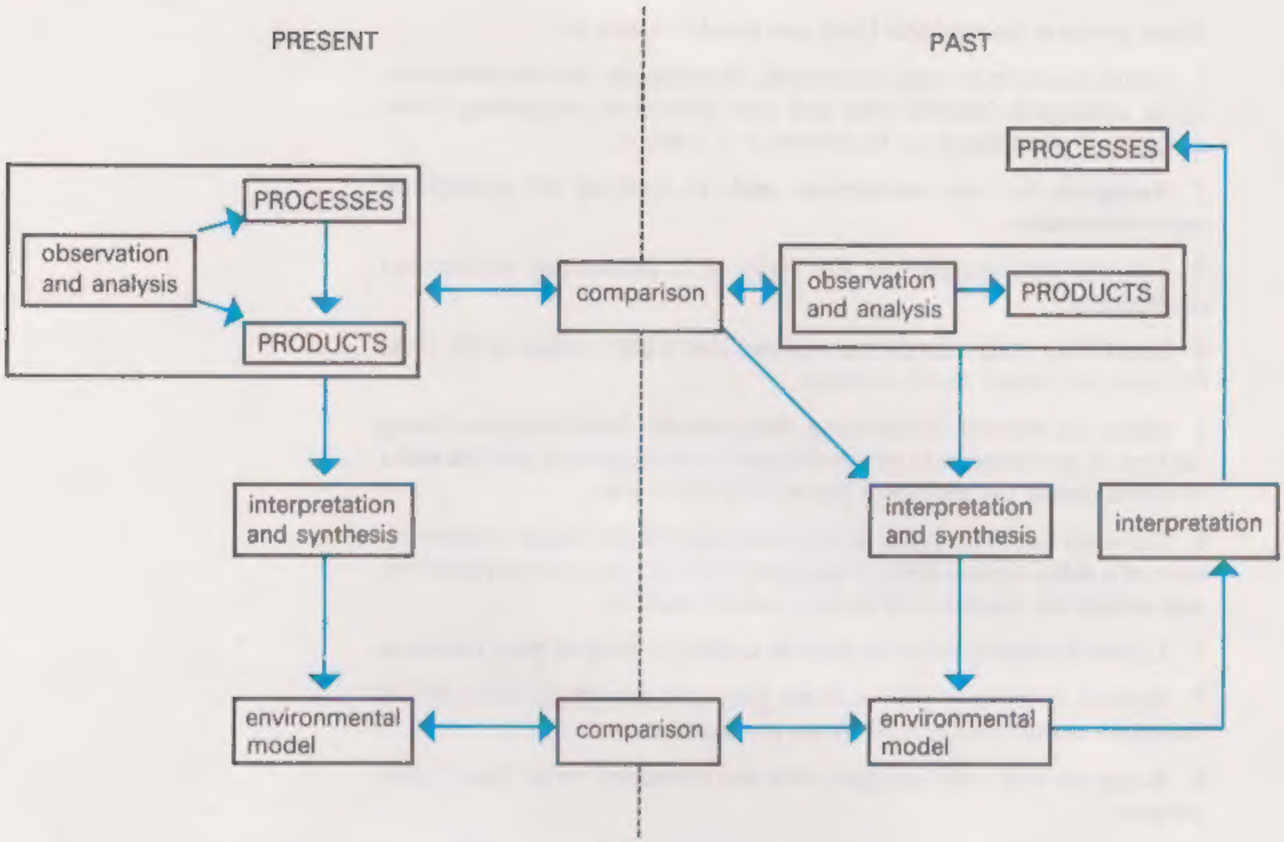

PRESENT
PAST
PROCESSES
observation and analysis
PRODUCTS
comparison
observation and analysis
PRODUCTS
PROCESSES
interpretation and synthesis
interpretation and synthesis
interpretation
environmental model
comparison
environmental model

Table A

List of Scientific Terms, Concepts and Principles used in Unit 26

Taken as pre-requisites			Introduced in this Unit			
1	2		3		4	
Assumed from general knowledge	Introduced in a previous Unit	Unit No.	Developed in this Unit	Page No.	Developed in a later Unit	Unit No.
astronomer	lava	24	present is key to past	9		
topography	sand	24	uniformitarianism	9		
flora	mollusca	21	environmental model	10		
fauna	processes	24	energy of environment	12		
coast	stratigraphic column	25	permeability	14		
salinity	pH	9	porosity	14		
	oxidation	8	Cenozoic	17		
	reduction	8	Mesozoic	17		
	ecology	20	Palaeozoic	17		
	mineralogy	24	Phanerozoic	18		
	texture	24	Precambrian	18		
	climatic belts	25	andesites	19		
	fossil	19	granites	19		
	delta	24	arkoses	21		
	Alpine-Himalayan chain	25	greywackes	21		
	circum-Pacific belt	25	cross-stratification	25		
	lithosphere	22	law of superposition	25		
	plate margins	25	lithostratigraphy	25		
	folding	24	correlate	26		
	faulting	24	law of faunal succession	26		
	sediments	24	younging	26		
	quartz	24	biostratigraphy	27		
	feldspar	24	era	32		
	ferromagnesian minerals	24	period	32		
	pyroxene	24	system	32		
	amphibole	24	type section	32		
	geochemical cycle	24				
	radiometric dating	2				
	metamorphism	24				
	orogenic belt	24				

Any scientific terms used in this Unit but not listed are marked thus † and defined in the glossary (p. 24).

26.1 The Present is the Key to the Past

26.1.1 Introduction

Flowing water must have eroded land masses in the past, much as it does today. So sediments must have been deposited in the past in much the same way as similar sediments being laid down today. In making these statements we are assuming that the physical and chemical laws that can be defined on the Earth today have been the same throughout the Earth's history. Astronomers make the same kind of assumption when they maintain that physical laws are the same throughout the Universe.

The principle of uniformitarianism maintains that present-day physical and chemical laws have not changed through geological time. Using this principle, we assume that processes active on the Earth today have always been active, so that to study the past we must study the present: the *present is the key to the past*. If this assumption is incorrect, inconsistencies will soon appear. Earlier Units have involved the principle of uniformitarianism, by extending back through geological time our observations concerning earthquake distribution patterns and the magnetic properties of the Earth.

uniformitarianism

the present is the key to the past

Observations of present-day processes thus give us clues as to how rocks were formed many millions of years ago. Laboratory studies of ancient rocks enable their physical and chemical compositions to be precisely defined, and field investigations reveal their distribution. Rocks forming at the present day are amenable to exactly the same kinds of investigation but, in addition, the processes leading to their formation may also be studied. For example, lavas erupted by volcanoes may be studied both while they are still molten and after they have cooled to form rock.

Similarly, environmental factors such as water turbulence and tides, which affect the formation of beach sands, may be investigated, as well as the sediment itself. In both these present-day examples, rock type may be related to conditions of formation. When studying ancient rocks, the assumption is made that they formed under conditions similar to those producing their modern equivalents.

You may think this is all rather obvious, but the idea that the present is the key to the past was revolutionary at the beginning of the nineteenth century. Even with the development of mining technology in the sixteenth, seventeenth and eighteenth centuries, religious dogma dominated the interpretation of the rock record and scientific reason had to be reconciled with 'Earth history' as recorded in the book of Genesis. For this reason James Hutton, the Scottish geologist who first proposed uniformitarianism, experienced great difficulty at the end of the eighteenth century in convincing other natural scientists that the processes which can be observed on the Earth's surface could, given sufficient time, account for all the features observed in ancient rocks. In Saxony, at about the same time, Abraham Werner was developing the theory that *all* rocks, even granites and basalts, were precipitated from a primeval sea. The fact that this 'Neptunist' school (named after the Greek god of the sea) was dominant for over thirty years can be attributed almost entirely to Werner's persuasive skill as a lecturer, and the persistence of religious influence on scientific thought during the late-eighteenth-century 'Age of Reason'.

However, with the publication of *Principles of Geology* by another Scotsman, Charles Lyell, in 1830 the fate of the Neptunist was sealed. Lyell marshalled much evidence in support of Hutton's theory that rocks could be interpreted in the light of natural laws without invoking either divine intervention or catastrophic events. Lyell is often referred to as the 'father of historical geology'. As a result of his influence, many of the important developments in geology were accomplished by geologists working in Britain.

26.1.2 A modern coastal environment

The idea of interpreting the past in terms of the present sounds extremely simple, but there are many practical difficulties. An insight into the extent of these can be gained by considering a present-day environment from a geological point of view.

So, you should now read the section in Chapter 13 of *Understanding the Earth* entitled 'environmental analysis—the beach' (pp. 180–5).

When you read this section, examine Figure 14 in Appendix 3 (p. 34), which summarizes information on the sediments and faunas of a modern beach. Plate A and TV programme 26 are about this area. *Make sure you have examined Figure 14 thoroughly and have read pp. 180–5 of* Understanding the Earth* *given above before viewing the television programme.* The post-broadcast notes will refer you to Appendix 3 which describes a 'geological model' of this stretch of coast and summarizes the sequence of 'rocks in the making' in this environment.

Either now, or after you have viewed the TV programme, consider what you would measure on a present-day beach in order to describe quantitatively such an environment; pay particular attention to the materials and processes which would be preserved when the sediments became rocks.

You should compile your list under the following headings.

(1) Topography

(2) Climate

(3) Water conditions

(4) Flora and fauna

(5) Sediments

DO NOT READ ON UNTIL YOU HAVE ATTEMPTED TO MAKE A LIST.

* *See glossary (Appendix 1) for unfamiliar terms in set reading.*

For the beach environment you should have considered measuring some of the following.

	Defined and/or discussed in: Unit Section No.	Defined and/or discussed in: Understanding the Earth
1 *Topography*		
(a) Elevation of different sediment types (in 5) above mean sea-level, and type of surface they form—hills, dunes, flats, cliffs.		p. 181
2 *Climate*		
(a) Temperature variations: daily, seasonal and annual, in both the air and sea. (b) Rainfall. (c) Amount of sunshine.	25.1, 20.2	
3 *Water Conditions*		
(a) Salinity (usually expressed in parts per thousand as a weight ratio of dissolved salts to water).		
(b) Composition of dissolved salts.		
(c) pH.	9	pp. 178–9
(d) Oxidizing or reducing conditions.		
(e) Flow conditions: tidal, drainage, etc.	TV 26	
4 *Flora and Fauna*		
(a) Identification of plants and animals present (living and dead).	20	
(b) Quantitative study of the distribution of plants and animals present.	20.1, 20.2	
(c) Ecological studies in relation to the features of the environment.	20.3, 20.4, 20.5	
5 *Sediments*		
(a) Mineral composition.	24	
(b) Grain size, sorting, shape (texture).		pp. 168–70
(c) Internal and external structure, such as cross stratification and ripple marks.		pp. 170–6
(d) Organic remains: flora and fauna.		

None of these headings can be considered in isolation. For instance, flow conditions influence the type of sediment deposited, and water conditions together with climate will influence the types of flora and fauna that can flourish in a given region.

Which of the features listed above do you think might be available several million years hence for future geologists to examine?

The only heading on the list above that you could say very much about would be the sediments (5), which are the products of processes occurring within an environment. It is possible that some elements of the flora and fauna would be preserved after death, as fossils, but the population so preserved might not show much resemblance to the original living population, either because of peculiar reasons for its death, or because it was transported after death—but mainly because only certain materials are suitable for preservation as fossils. For example, the shells you saw in the first part of TV 24 are only the hard external skeletons of mollusca. The soft parts of animals are rarely preserved, and then only as impressions, while the calcareous shells may be dissolved after burial. Normally, however, it is the hard parts which are preserved as fossils.

Thus there is a considerable difference between the list of things you could observe at the present time in a given environment, and what would be left behind in the fossil record of such an environment. We cannot directly measure the amount of rainfall, or temperature, or salinity for a given past environment, but we can attempt to interpret the sedimentary record in terms of such factors. Remember in Unit 25, section 1.3, Figures 6 and 7, we indicated that certain distinct types of sedimentary rocks characterize certain climatic belts.

Now read Appendix 3, which describes a geological model and summarizes the rock record deposited in a coastal environment (make sure you have viewed this Unit's TV programme first).

26.1.3 Energy of environment

Any feature of sediments and their faunas and floras can be related to what is called energy of environment. This is easier to describe in terms of an actual example, so we shall return once more to the coastal environment. High energy conditions are characterized by the surf zone, where waves are constantly breaking and producing turbulent currents of extremely high velocity.

energy of environment

In contrast to this, low energy conditions exist in sheltered marsh areas, which are seldom affected to any degree by tidal currents, or by wind-driven water currents. The sediments in these two regions differ markedly, as the photographs in Figure 1 and the illustrations in Plate A show.

What would you expect to be the main differences between sediments accumulating in the high and low energy zones in terms of (a) overall grain size; (b) range of grain sizes (sorting); (c) shape of the grains?

The main differences are as follows. (a) The beach sediment is much coarser (large grain size) and the marsh sediments are much finer (small grain size). (b) On the other hand, the actual *range* of grain sizes is much smaller in the high-energy beach environment than in the low-energy marsh environment. (c) Particles in the beach environment are more likely to be rounded than those in the marsh environment. These contrasts are explained below.

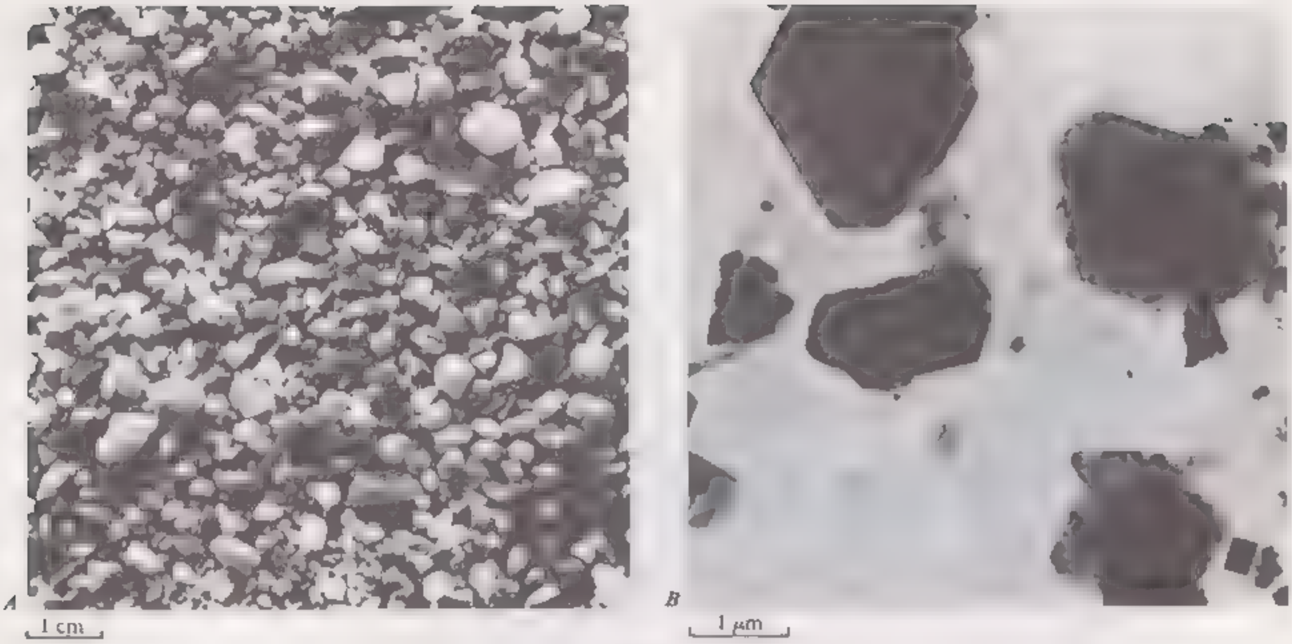


Figure 1 Contrasting grain sizes of sediments accumulating in a high energy environment (A: gravel) and a low energy environment (B: clay minerals).

The extreme turbulence, or energy, of the beach environment winnows away the finer material, leaving a sediment in which the spaces between the larger grains are empty but interconnected. In the marsh environment, where there is a greater range of grain sizes, spaces between larger grains are occupied by smaller grains. Hence, the inter-grain spaces which remain are not interconnected. The effect of duration of processes on the character of sediments is also important. If high-energy conditions persist only for brief periods, they can have little effect on the final character of the sediments. But in the beach environment, the waves are breaking constantly on the sediment, so the winnowing process is continuous and can proceed to completion. This time factor is demonstrated very well by experiments in which small quartz cubes are subjected to abrasion in a wind tunnel to simulate wind transport. Given sufficient time in the wind tunnel, the cubes gradually have their corners worn away due to successive collisions with each other (Fig. 2) and eventually become spherical in shape. In general then, the longer a sedimentary grain remains in a high-energy environment, as simulated by the wind tunnel, the more rounded it is likely to become.

Figure 2 Small cubes of quartz which have been subject to abrasion in a wind tunnel to simulate transport in natural environment. The cubes become increasingly rounded off towards the right reflecting the longer periods that they remained in the experiment.

Sediments laid down in high-energy conditions, therefore, consist of fairly coarse, fairly well sorted and rounded grains. Those in low-energy conditions are finer grained and less well sorted, and the grains are angular rather than rounded (Fig. 3).

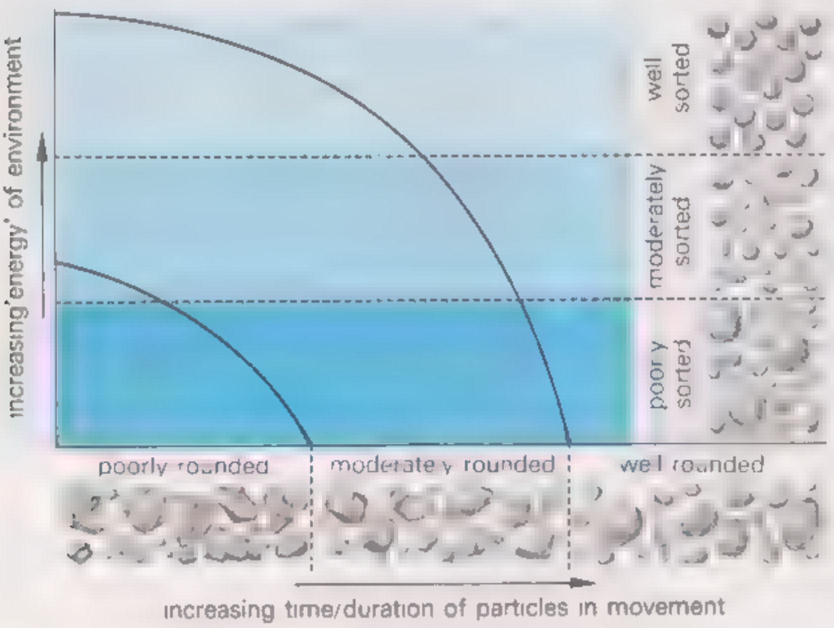


Figure 3 Diagram summarizing the effect of 'energy' of environment and the time grains remain in it in influencing their final shape and sorting. Grain size is not shown on the diagram.

26.1.3.1 Porosity and permeability

Porosity is the amount of empty pore space between the grains in a sediment. Permeability is a measure of the extent to which the empty spaces are interconnected to permit water and other fluids to pass. The actual amount of empty pore space (porosity) in sediments may be very high, as much as 80 per cent in some cases, irrespective of whether they have formed in high- or low-energy conditions. In well sorted, high-energy sediments the empty spaces are interconnected, so that fluids can pass easily through them—such sediments are permeable. In contrast, sediments from low-energy environments are impermeable because, although they may have plenty of empty spaces between the grains, those spaces are not interconnected. Figure 4 summarizes the relationships between porosity and permeability.

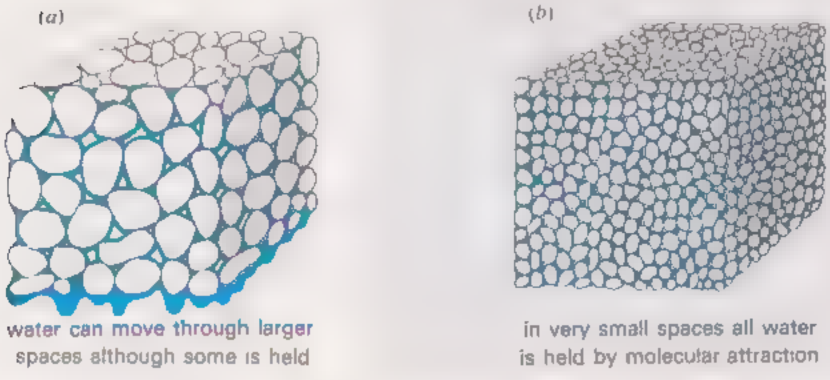


Figure 4 Porosity and permeability: in coarse grained sediments, water can flow between individual pore spaces (a), *but in fine grained sediments, molecular attraction holds water within the pore spaces, preventing flow* (b). *In the latter case, very high porosity may be accompanied by negligible permeability.*

26.1.3.2 An economic implication

High porosity, when it occurs together with high permeability in fossil sediments, is often of great economic significance. The porosity of such rocks means that the voids may be occupied by oil, water or natural gas, and the permeability means that these fluids can flow through the rock bodies, and so can be extracted. It is for this reason that the oil geologist is particularly interested in finding sediments laid down in high-energy environments (and not just those of the coastal environment we have used as an example). Such sediments have the potential of being reservoir rocks for oil, gas or water, which are stored in the pore spaces. By studying the distribution of such high-energy sediments in modern environments, it is possible for the oil geologist to make predictions about the geometry of potential reservoir bodies in ancient sediments.

porosity

permeability

What is the geometry of high-energy conditions in a coastal environment?

If you examine the chart of the coastal environment in Appendix 3, you will see that the high-energy sediments (beach and dune deposits) are distributed in long narrow belts whose orientation is largely influenced by the prevailing wind direction. Sediments laid down in deltas have more complicated but equally characteristic geometry, described in pp. 185–8 of *Understanding the Earth*, which you should now read.

26.1.4 Examples of other methods used in reconstructing past environments

There are several new methods of investigating rocks and minerals in order to reconstruct their past environment. For instance, it is known from measurements made on present-day invertebrate shells that the ratio of the two isotopes of oxygen present in the shells of invertebrate animals is related to the temperature of the waters in which they live. Palaeontologists have made similar measurements on fossil shells as much as 100 Ma old, and deduced from these measurements the temperature of ancient seas to within 1° C. Similarly, modern corals develop daily growth-bands in their calcareous skeletons (Fig. 5) which appear to be

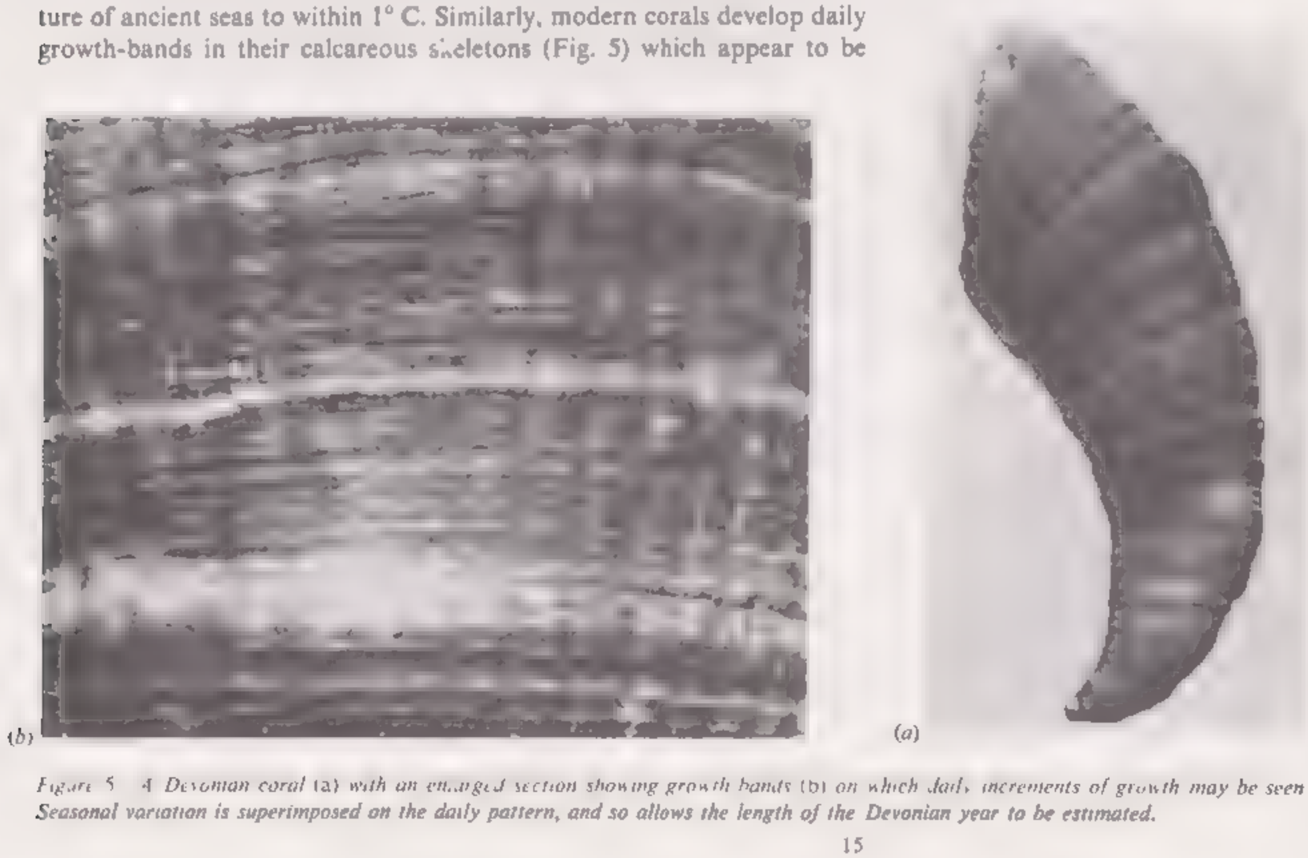


Figure 5 A Devonian coral (a) with an enlarged section showing growth bands (b) on which daily increments of growth may be seen. Seasonal variation is superimposed on the daily pattern, and so allows the length of the Devonian year to be estimated.

controlled by the rise and fall of the tide. As seasonal variations are superimposed on this pattern, it is possible to follow the yearly growth of a particular coral. Comparable banding has been discovered in fossil corals, and growth-ring counts of Devonian corals (Fig. 5) suggest that 400 Ma ago an Earth year had a duration of 400 days. This palaeontological finding is of particular interest to geophysicists for it is quantitative support for their deduction that the Earth's speed of rotation is decreasing due to tidal friction (see *Understanding the Earth*, pp. 110–11).

Igneous and metamorphic rocks can also be studied from the uniformitarian point of view. Igneous rocks being formed in volcanic regions at the present time are amenable to observation in the field and laboratory, in the same way as are sedimentary rocks, and Earth scientists can attempt to reproduce the conditions of their formation in the laboratory. With metamorphic rocks it is more difficult, since these have generally formed at depth under high pressure and temperature conditions, so that they cannot be observed in the process of formation. But it is precisely because we can supplement our field observation with laboratory experiment, that we are able to say that metamorphic rocks *do* form under high pressure and temperature conditions.

26.2 Interpreting the Rock Record

26.2.1 The stratigraphic column

The ability to equate rock successions in different locations, using some sort of time scale, is an essential step towards constructing a picture of past environments. After all, it would be impossible to write an account of British history without including dates! So, if we want to say something about conditions existing in Britain in Carboniferous times (about 350 Ma ago), we must be able to recognize Carboniferous rocks. Table 1 summarizes the divisions of the geological time-scale and the derivation of the terms used. YOU ARE NOT EXPECTED TO LEARN THESE TERMS.

Table 1 THE STRATIGRAPHIC TABLE

*Eras**	*PERIODS AND SYSTEMS*	*Age of base in Ma (used in this course)*	*Country where defined*	*Author*	*Year*	*Derivation*	
	QUATERNARY						
	Recent or Holocene					Holos: whole	
	Pleistocene		UK	Lyell	1839	Pleiston: most	
	TERTIARY						
	Pliocene**		UK	Lyell	1833	Pleios: more	Derived from Greek descriptions refer to proportion of present-day species present in fossil faunas.
CENOZOIC (*Recent life*)	Miocene**		UK	Lyell	1833	Meion: less	
	Oligocene**		G	Beyrich	1854	Oligos: few	
	Eocene**		UK	Lyell	1833	Eos: dawn	
	Palaeocene**	65	G	Wilhelm Schimper	1874	Palaios: old	
	CRETACEOUS	136	F	d'Halloy	1822	Creta: chalk	
MESOZOIC (*Middle life*)	JURASSIC	190	S	Humboldt	1795	Jura Mountains	
	TRIASSIC	255	G	Alberti	1834	Threefold division recognized in Germany	
	PERMIAN	280	R	Murchison	1841	Perm: Russia	
UPPER	CARBONIFEROUS	345	UK	Conybeare and Phillips	1822	Coal: Carbon	
PALAEOZOIC (*Ancient life*)	DEVONIAN	395	UK	Murchison and Sedgwick	1840	Devon	
	SILURIAN	440	UK	Murchison	1835	Silures: Welsh border Celts	
LOWER	ORDOVICIAN	500	UK	Lapworth	1879	Ordovices: Celts of N. Wales	
	CAMBRIAN	570	UK	Sedgwick	1835	Cambria: Roman for Wales	

Key F = France; UK = United Kingdom; S = Switzerland; G = Germany; R = Russia

* *The Italian Arduino defined these in 1760, and Secondary is still sometimes used for Mesozoic.*

** *Lyell recognized that in the Tertiary, modern species appear as fossils, becoming more abundant in younger sediments (e.g. 3 per cent of Eocene species are alive today, and as many as 30–50 per cent of Pliocene species exist today).*

NOW READ APPENDIX 2 'THE STRATIGRAPHIC COLUMN' (p. 25).

26.2.2 The Phanerozoic

Phanerozoic, literally translated from the Greek, means 'showing life'—life in fact as we know it today. To stratigraphers, the Phanerozoic is the period of geological time extending over about the last 600 Ma, during which organized life with hard parts has existed in a form very similar to that which we know today. Phanerozoic rocks are those in which we can find fossils of organisms which possessed hard parts of shell or bone; such fossils are unknown in rocks older than the Phanerozoic. These rocks, older than about 600 Ma, are called *Precambrian* rocks. Simple organisms, such as algae and bacteria, are known from rocks over 3 000 Ma old, and imprints of organisms with no hard parts have been found in very late Precambrian sediments (Fig. 14.8 of *Understanding the Earth*). As organisms with hard parts have only existed for the relatively short period of 600 Ma, most of our detailed knowledge of past epochs has been confined to the Phanerozoic, for without fossils precise correlation of strata in different locations is very difficult.

The next two sub-sections give two examples of how events in the Phanerozoic record may be investigated. The first gives some idea of the painstaking work needed to build up a picture of past environments—in this case, the Carboniferous Period. The second widens the scale, and enquires if the principle of uniformitarianism can be invoked to explain global features such as fold mountain chains.

26.2.3 The Carboniferous in Britain

NOW READ PP. 188–91 OF CHAPTER 13 OF *UNDERSTANDING THE EARTH*.

As before, you are not expected to remember the details, but you should get some insight into the methods of investigation used to construct past environments. The stratigraphic evidence for continental drift, discussed in Unit 25, was accumulated in a manner similar to that described by Professor Walton.

After you have read pp. 188–91, you may like to try Self-Assessment Questions 7 to 10, to ascertain how well you have understood this material. Factual recall is *not* expected.

26.2.4 Orogeny and uniformitarianism

Uniformitarianism is basic to the Earth sciences; we can interpret ancient sedimentary environments by comparing their features with those of the present day. Volcanologists use the principle to explain old volcanic sequences in terms of the products and processes of historically active volcanoes. Palaeontologists investigate present-day ecology to explain why certain fossils are found in certain types of sediment, and geomorphologists invoke uniformitarianism to explain how ancient land forms developed.

All these are small-scale processes and products in terms of global dimensions—can we apply uniformitarianism on a large scale to the major surface features of the Earth? In Unit 25, the theory of plate tectonics was proposed as the most acceptable framework within which

to explain the Earth's major surface features. It was shown how measurements of present-day seismic activity, and of the geomagnetic field during the last few million years, could be extended through space and time to explain the behaviour of the Earth's crust. The plate tectonics theory explains the present movements of the crust and can be used to interpret the last 200 Ma of Earth history, but can we apply it still further back in time? In the remainder of this Unit, we shall look at the Earth's present-day fold mountain chains, examine how they formed in the context of plate tectonics, and then see if, by applying uniformitarianism, we can reconstruct the development of older orogenic belts.

Remember that the plates have three types of margins, *constructive*, *destructive* and *conservative*, and that there are two major belts of young fold mountains—the Circum-Pacific belt† and the Alpine-Himalayan chain.† With which type of plate margins are these two mountain chains associated? Indicate your choice by ticking in the appropriate column.

	Circum-Pacific belt	Alpine-Himalayan chain
1 Constructive margin		
2 Conservative margin		
3 Destructive margin (ocean meets continent)		
4 Destructive margin (continent meets continent)		

Your answer should be destructive margin in both cases; the circum-Pacific belt overlies a zone where an oceanic plate underrides a continental plate (3) whereas the Alpine-Himalayan Chain has been formed where continent meets continent (4).

So it is destructive margins we must examine closely. There are differences in the type of deformation (that is, folding and faulting) that occurs when continent meets continent, as against that produced where an oceanic plate underrides a continental plate. The examination and explanation of such differences is beyond the scope of this Unit, so we will take the simpler case, the margin between continental and oceanic plates.

26.2.4.1 Features of 'young' fold mountain chains at continent/ocean boundaries

There are four main processes operating at the leading edge of a continental plate (the edge which overrides the descending oceanic plate). (1) igneous; (2) metamorphic; (3) deformational; and (4) sedimentary.

1 *Igneous processes*

As the oceanic plate passes deeper into the Earth's mantle it becomes hotter. This heat passes upwards both by conduction and (more rapidly) by passage of molten rock liquids, some of which escape at the surface as lavas to produce volcanic rocks. These are of a special variety known as *andesites*, after the Andes where they are abundant, and are probably generated by the partial melting of sediments and oceanic crust as the down-going plate moves deeper into the mantle. They are composed of feldspar and the ferromagnesian minerals (pyroxene and amphibole) together with some quartz, and are abundantly found only in orogenic belts. The heat is intense enough to melt partially some of the sialic rocks of the continental plate, producing liquids of granitic composition which aggregate together, move upwards, and subsequently crystallize higher in the crust as granite. The heat generated in all these processes is produced along a narrow belt some 200 km wide all along the length of the leading edge of the advancing continental plate.

2 *Metamorphic processes*

Rocks of the continental leading edge are subjected to high temperatures and stresses due to the opposing plate movements, and become metamorphosed. Metamorphism covers both the mineralogical and structural changes brought about by changes in the physical environment. The original minerals, which are stable at low temperatures and pressures, must convert to minerals stable at elevated temperature or pressure or both. The areas affected by this alteration are so large that it is termed *regional metamorphism.* The roles of temperature and pressure vary within the linear zone along the continental leading edge. For instance, at the extreme leading edge of the continental plate, where cold continental plate meets cold oceanic plate, pressures are high but the temperatures are low—there is therefore a frontal zone of low-temperature/high-pressure metamorphism. Behind this cold region, the continental plate is heated by friction between the two plates and this heat passes upwards to produce a higher temperature metamorphism.

regional metamorphism

3 *Deformation processes*

The large-scale effects of fracturing and folding of rocks are usually considered under the general heading of deformation, and we refer to the features produced as *tectonic structures.* The type of structures produced varies: in the cold, high-pressure frontal zone, solid rocks tend to break and fracture; whereas in the high-temperature rear zone, rocks bend and fold.

tectonic structures

There are many common substances that fracture when cold and bend when hot. Can you think of any?

A bar of toffee warmed in the hand will bend easily, but is difficult to break. If you cool it in a refrigerator, it will break easily. Even warm toffee can be broken, however, if you give it a sharp blow, e.g. with the back of a spoon. This introduces the factor of *time.* Rapid deformation, which in this case is produced by the blow with the spoon, causes fracturing; slow deformation, using your hands, causes bending. The same applies to the Earth; rapid deformation results in faulting, slow deformation in folding. So, by examining the structures in rocks, we can often deduce whether the environment was hot or cold, and whether the deformation was slow or rapid.

4 *Sedimentary processes*

The continental sides of destructive plate margins possess high relief, and are therefore subject to rapid and intense erosion. The composition of sediments deposited in any environment is controlled by the following four main factors.

1 The distance they have to travel before being deposited.
2 The climate of the region of erosion.
3 The composition of the rocks eroded.
4 The elevation of the region of erosion.

In these orogenic belts, however, the composition of the eroded rocks is by far the most important factor. Rapid erosion does not allow time for climatic conditions greatly to modify the composition of the rocks before or during the erosion process. As the distance the sediments travel will most likely be small, they will be generally poorly sorted and there will be little time for unstable minerals to break down. The elevation of the region has a large control over the quantity of debris produced, but has little effect on the composition of the sediments.

What rocks are available for erosion to produce sediments? Indicate your choice on the list below, checking back through this section if necessary.

1 Andesites

2 Granites

3 Metamorphic rocks

4 Ocean floor basalts

5 Folded sediments

6 Peridotites

7 Ocean floor sediments

You should have selected 1, 2, 3 and 5. Peridotite (6) is the main constituent of the upper mantle, while (4) and (7) are obviously not available for erosion.

The sediments produced from andesites contain feldspar, quartz and ferromagnesian minerals. The latter generally become altered to clay minerals (see TV 24 notes), which form the matrix to the other mineral fragments. Such sediments are called *greywackes*. They also characteristically contain a proportion of rock and mineral fragments derived from the metamorphosed and deformed sediments. Greywackes are transported by turbidity currents (Unit 24, p. 40) and are poorly-sorted, fragmental rocks.

greywackes

Sediments derived from granite are primarily composed of quartz and (alkali) feldspar and are called *arkoses*. Often these sediments are coarse-grained rocks which, in turn, reflects the coarse-grained nature of their source rock, and the short distance the rock debris travels before deposition.

arkoses

26.2.4.2 Summary to section 26.2.4

Figure 6 outlines the disposition of the two plates at a destructive margin. Insert into this figure the sites of the following processes and products by placing the appropriate letter alongside the items on the list.

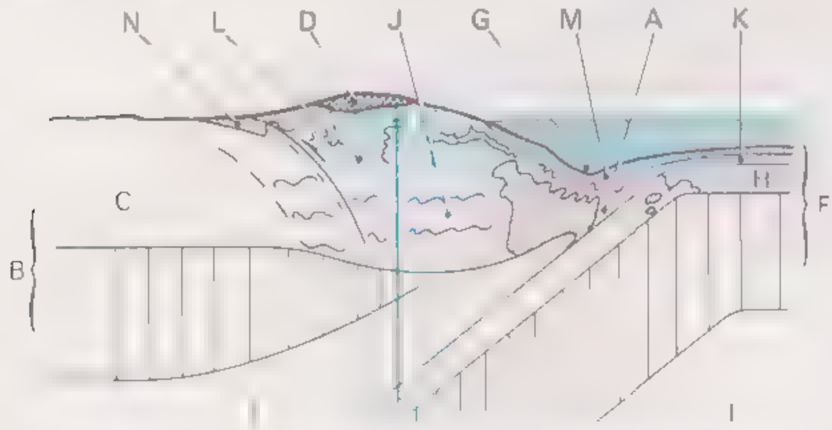


Figure 6 Idealized section through a destructive plate margin: to be completed by the student from instructions in the text.

1 The oceanic plate
2 The continental plate
3 The asthenosphere
4 The oceanic trench
5 The continental crust
6 The oceanic crust
7 Zone of high-pressure, low-temperature metamorphism
8 Zone of higher temperature metamorphism
9 Zone of andesite magma generation
10 Area of andesite volcanics
11 Zone of granitic magma genesis
12 Area of arkosic sediments
13 Region of greywacke sedimentation
14 Zone of ocean floor sediments

Once you have completed this diagram you can check it with Figure 20.4 in *Understanding the Earth*. By completing Figure 6, you will realize that in the zones overlying destructive plate margins there are a variety of rocks, zones and structures that are created by the destruction of the oceanic plate; these are as follows.

1 Greywacke sediments formed from the erosion of andesites and metamorphosed and folded sediments.

2 Arkosic rocks produced by the erosion of granites.

3 The whole zone is a linear belt of deformation with the major trends of deformation parallel to the leading plate edge.

4 A linear belt of igneous activity characterized by the eruption of abundant andesitic volcanic rocks and the emplacement of large granite masses.

5 Linear zones of regional metamorphism with a belt of low-temperature/high-pressure metamorphism lying nearer the plate margin and a zone of higher temperature metamorphism occurring further inland.

Looking back through geological time we find linear zones which, although they do not necessarily contain all the features listed above, contain sufficient to suggest strongly that they are 'fossil' plate margins.

About 400 Ma ago, a linear belt was formed stretching east and west across Europe, and called the Hercynian orogenic belt† (see Unit 24, Fig. 9, key 4). Between 600 and 400 Ma ago another belt, the Caledonian orogenic belt† was formed (Unit 24, Fig. 9, key 3), stretching from Scandinavia, south-west through Scotland, northern England, Wales and into Canada and the USA. Both these belts are characterized by greywackes, regionally metamorphosed sediments, much folding and faulting, and many granite bodies. There are other examples of even older orogenic belts, suggesting that plate tectonics has probably always been a major process in the development and modification of the Earth's major surface features.

Summary

By assuming that the physical and chemical laws that hold on the Earth today have been the same throughout geological time, we are able to explain the origin of ancient rocks in terms of the origin of their modern equivalents.

Examination of a modern coastal environment shows how the sedimentary features form an assemblage diagnostic of that environment, though individual sedimentary types could well be found in a variety of settings. A case study of deltaic sediments shows the strict comparability of modern and ancient sediments deposited in this environment.

Leading from the seemingly obvious statement, inherent in the law of superposition, that in a sequence of layered rocks the ones above are younger than those below, the younging direction of a sedimentary rock can be deduced. A sequence of rocks deduced from one area has then to be correlated with sequences elsewhere by means of lithostratigraphy, biostratigraphy and radiometric dating. By these means a stratigraphic column of world-wide application can be erected.

Most exercises in 'uniformitarianism' are small scale: beaches, deltas, volcanoes, etc. Within the framework of plate tectonics, an attempt is made to relate the processes and products at a destructive plate boundary, and recorded in the rocks and structures of the young fold mountains, to those of the older orogenic zones which, it is proposed, are fossil plate boundaries.

Further Reading

If any of the topics discussed in this Unit particularly interested you, you may like to read a selection of the following (as black-page material).

1 *Understanding the Earth*

Chapter 2, 'Measuring geological time'
Chapter 13, 'Looking back through time'
Chapter 20, 'Orogeny'

2 C. R. Longwell, R. F. Flint and J. Sanders, *Physical Geology*. John Wiley, 1969.

Chapter 6, 'The Geologic column and Geologic time'
Chapter 16, 'Sedimentary strata'

3 A. Holmes, *Principles of Physical Geology*. Thomas Nelson, 1965.

Chapter 7, 'Pages of Earth History'
Chapter 13, 'Dating the pages of Earth History'

4 *Scientific American Reprints*. W. H. Freeman and Co.

S. K. Runcorn, 'Corals as palaeontological clocks'. No. 871.
Ph. H. Kuenen, 'Sand'. No. 803.
C. Emiliani, 'Ancient Temperatures'. No. 815.

Appendix 1

Glossary

ALPINE-HIMALAYAN CHAIN The great east-west structural belt of igneous, metamorphic and deformed sedimentary rocks, which include the Alps of Europe and the Himalayas. These rocks were mostly deformed in Tertiary times.

ANASTOMIZING Branching.

BED The smallest division of stratified rocks, marked by more or less well-defined planar surfaces from its neighbours above and below. The bounding planes are termed *bedding planes.*

CALEDONIAN OROGENIC BELT The mountain system formed by a series of Earth movements in the Lower Palaeozoic. Named after the classic area in the Scottish Highlands where rocks deformed during this orogenesis were first investigated.

CHORDATES Animals possessing a bony spinal column.

CIRCUM-PACIFIC BELT A belt of igneous metamorphic and tectonically deformed sedimentary rocks that occur on the margin of the Pacific basin.

CORRELATE (CORRELATION) Determination of the equivalents in geological age and stratigraphic position of two formations, or other stratigraphic units, in separated areas; or more broadly, the determination of the contemporaneity of events in the geologic histories of two areas.

CROSS BEDDING Another term for cross stratification.

DIAGENESIS Process involving physical and chemical changes in a sediment after deposition, including compaction, cementation and recrystallization.

FACIES The total complex of all primary lithological and palaeontological characteristics of a sedimentary unit.

GEOSYNCLINES A large, generally linear, trough that develops along continental margins and accumulates, over long periods of time, thick successions of stratified sediments and possibly extrusive volcanic rocks.

HERCYNIAN OROGENIC BELT A mountain system stretching across central Europe formed by Earth movements in the upper Palaeozoic.

INTERCALATED Interbedded.

LAMINAE Very thin layering occurring in rocks.

LENTICULAR Lensoid shaped.

LITHIFICATION A complex of processes that converts a newly deposited sediment into an indurated rock. It may occur shortly after deposition, or it may occur long after deposition. Some sediments can be lithified within three or four weeks of their deposition, others remain sediments and unlithified for as much as 10 Ma.

PLANKTONIC ORGANISMS Organisms which float fairly passively in the sea or lakes.

PYROCLASTIC Term applied to detrital volcanic material erupted by explosive activity.

SALTATION The process by which sedimentary particles are transported by bouncing along a bed of sediment, rather than in continual suspension.

TERRIGENOUS SEDIMENTS Land derived sediments.

Appendix 2 (White)

The Stratigraphic Column

Steps in the construction of the stratigraphic column

There are three principle steps involved in constructing a stratigraphic column for a given region.

1 Examination of the physical characters and composition of the rocks (their lithology), and placing them in chronological order so that they may be compared with rock sequences elsewhere; this gives a *lithostratigraphy*.

lithostratigraphy

2 Lithological comparisons may be augmented by comparing fossil floras and faunas contained in the rocks. As assemblages of fossils change through time, it is possible to correlate the rocks, so determining those contemporaneous with each other.

3 Results obtained by the first two steps may be quantified by means of radiometric dating.

These three steps are described in more detail, as follows.

1 *Law of superposition and lithological comparisons*

law of superposition

Sedimentary rocks are deposited layer by layer on top of each other, so that the higher layers are younger than the lower ones. Earth movements may overturn sequences of these layered or stratified rocks. There are ways in which this can be detected. One commonly used method of determining whether a sequence of rocks has been inverted is to examine the geometry of *cross-stratified* sediments.

The TV programme of Unit 26 will show how such structures are formed, so for the moment a brief explanation, as given in Figure 7, will suffice. In Figure 7(d) there are two complete units of cross-stratification within

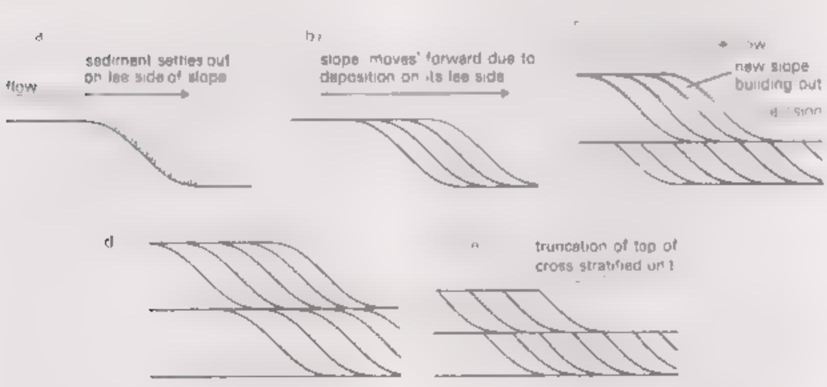


Figure 7 The formation of cross-stratification.

(a) Flowing water carries sediment particles in suspension and these are deposited out on the lee side of the slope, where the velocities are lower.

(b) Due to deposition on its lee side, the slope 'moves' forward producing 'layers' of the form indicated so producing a cross-stratified unit.

(c) After the formation of one cross-stratified unit, its top is eroded, and another formed above it.

(d) Two units of cross stratification formed without any erosion occurring.

(e) Two units of cross stratification produced by deposition and erosion, so that their tops are truncated.

a sandstone layer or bed.† The curve traced out by the cross-stratification resembles a rather flattened S viewed back to front. Because structures of this kind are produced by deposition of sediment from flowing water, erosion as well as deposition may occur. Figure 7 (e) illustrates just such a case, where the top part of each cross-stratified unit has been eroded before the deposition of the next unit. The curved layers of cross-stratification are therefore truncated at the top of each unit. Bearing this in mind

you should be able to identify the original top or younger layers of the sediments illustrated in Figure 8 A and B. The direction in which a rock sequence gets younger is termed the *younging* direction. Now try and identify the direction of younging in the three photographs shown in Figure 9.

There are other methods of determining the way-up of sediments, including graded bedding as described in *Understanding the Earth* (Fig. 13.12), but detailed discussion of these must await second-level courses in Geology. Thus equipped with the means to determine the 'younging' direction in a succession of strata, one can compile a list, from oldest to youngest, for any one area, as shown in Figure 10. The next step is to equate or correlate between successions in different areas and the simplest way of doing this is to compare the lithology of the rocks concerned. This involves setting up a stratigraphy based on lithological features of rocks: grain size, mineral composition, etc.—a *lithostratigraphy*.

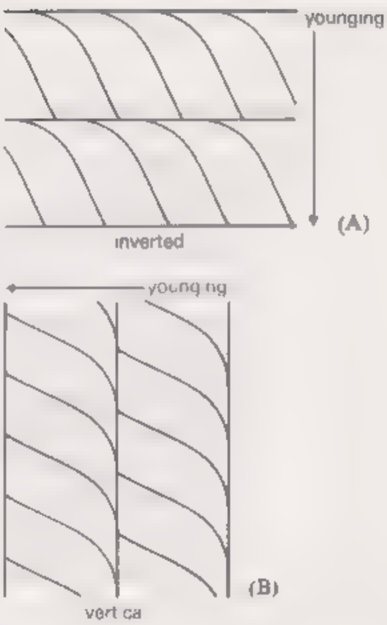
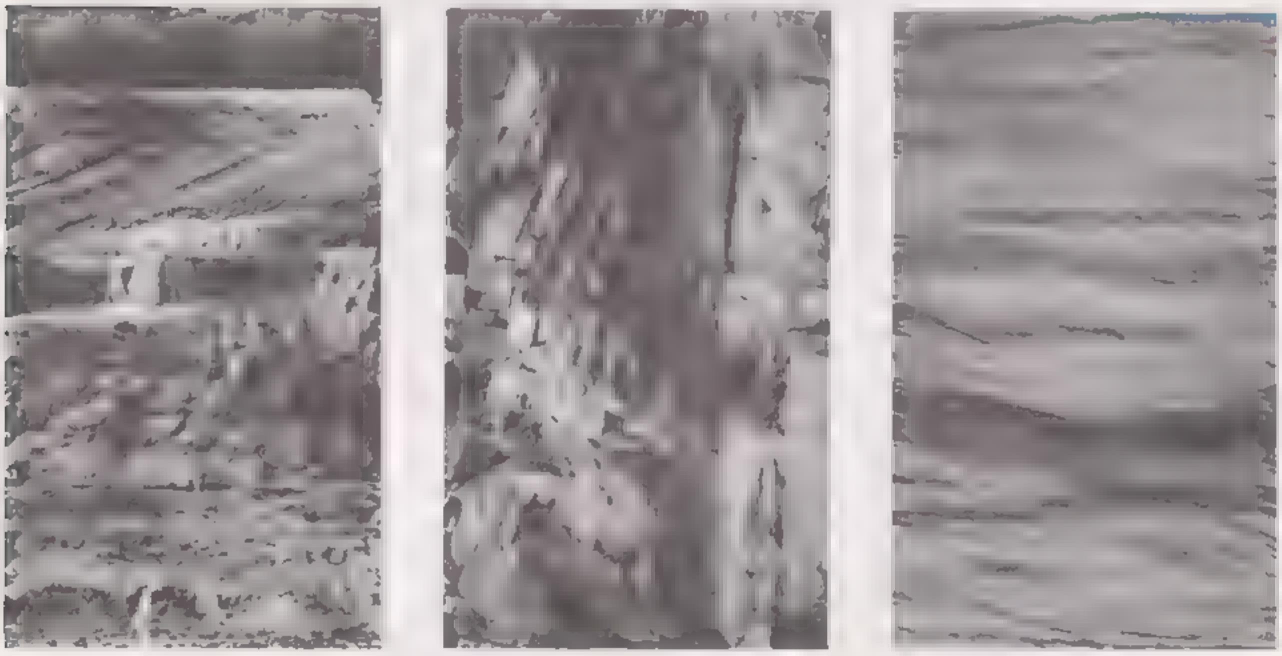


Figure 8 Determining the direction of younging in cross-stratified sediments.

2 *Law of faunal succession*

Law of faunal succession

This law states that fossil faunas and floras succeed one another in a definite order, and was discovered and applied by William Smith at the beginning of the nineteenth century. Smith used it as a tool to correlate the Jurassic (190–136 Ma) rocks of the Cotswolds, but did not attempt to



(*a*) (*b*) (*c*)

Figure 9 Photographs of cross stratification: in which direction are they younging? Insert an arrow beside each to show the younging direction (See page 32 for answers.)

explain why the method worked. However, with the publication of Darwin's *Origin of Species*, faunal succession could be explained in terms of continuous evolution rather than successive catastrophes by which one assemblage of species was killed off to be replaced later by another. Thus Darwin's evolutionary theory laid the foundation for modern methods in the palaeontological correlation of rocks, or *biostratigraphy*. Not only does biostratigraphy assume that successive faunas are produced by evolution and extinction, but that these events, in terms of the geological time-scale, are globally contemporaneous, i.e. they happen at the same time all over the world. (Those of you who continue to the second-level courses in the Earth sciences will learn more about biostratigraphic techniques.)

biostratigraphy

Figure 10 Stratigraphic succession as observed on the North Antrim Coast, Northern Ireland (described in detail in TV 27).

The end-product of such stratigraphic studies is that rock sequences can be placed in a relative time order with respect to each other. The article on the occurrence of tin cans and bottles in the refuse dumps of old American mining camps provides an excellent example using familiar objects. It is on pp. 37–40.

READ IT NOW AND THEN RETURN TO THIS TEXT.

As you read the article, you will have noted that the morphologies of cans, bottles and nails have changed through time. Try to summarize with sketches how the styles of these articles have changed with time. When you have done this, you end up with a 'range chart' and such a chart is shown in Figure 11 (a). Now some objects from mining camps will

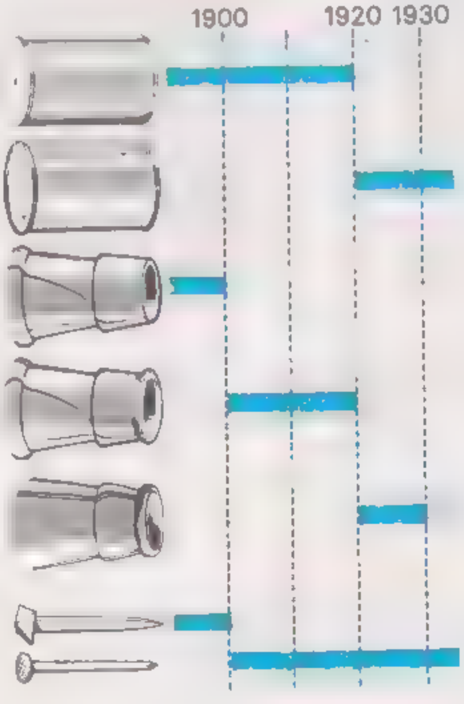


Figure 11 (a) Range chart for beer cans, beer bottles and nails in tip heaps of old American mining camps, compiled from article by C. B. Hunt in text.

be washed into rivers, and maybe end up in lake sediments. Figure 11 (*b*) summarizes the occurrence of a hypothetical case where this has happened and indicates the positions of 'fossil' cans, bottles and nails. Using the range chart, try to *correlate* the three sediment sequences given in Figure 11, and answer the questions below.

correlation

What is the age of the following?

	pre-1900	1900–1920	1920–1930	post-1930
1 The sands and gravels in sequence A.				
2 The sands and gravels in sequence B.				
3 The peat in sequence B.				
4 The sands and gravels in sequence C.				

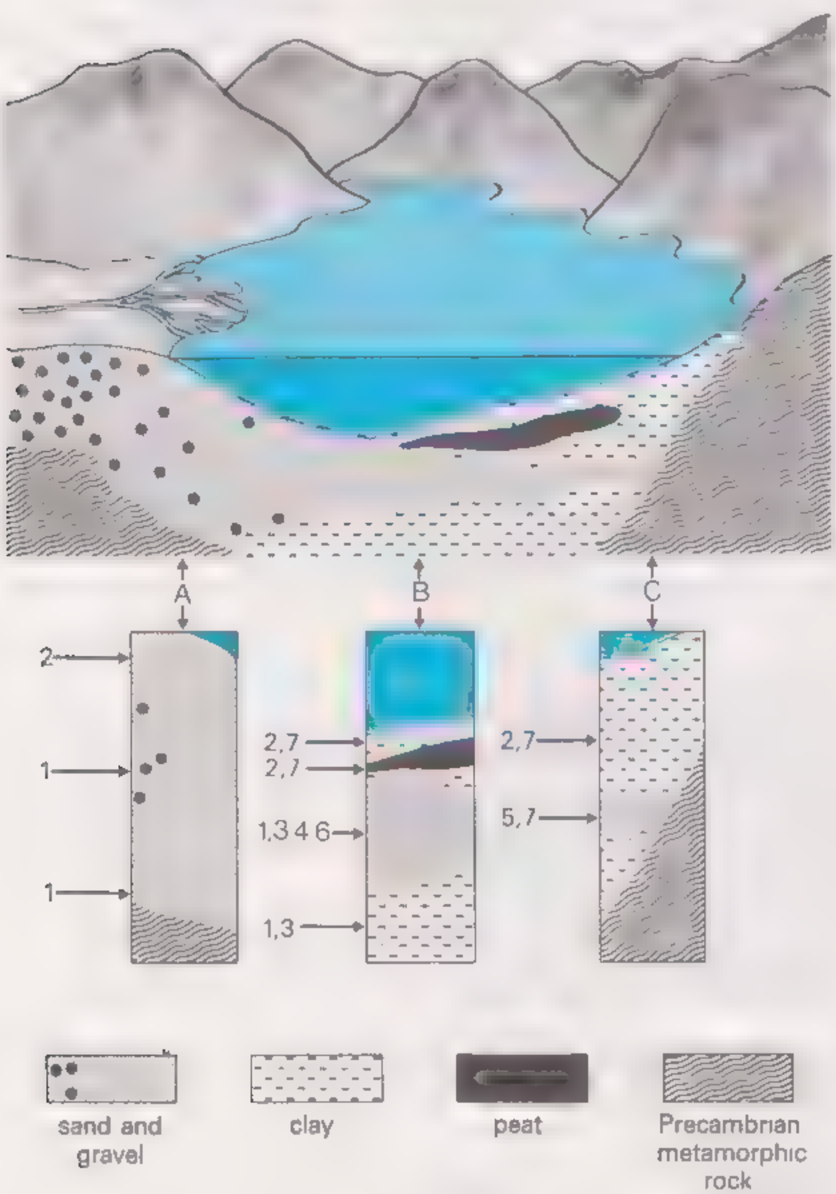


Figure 11 (b) Diagrammatic summary of lake deposits and their contained 'fossil' beer cans, bottles and nails. Sequences of lake sediments from three localities are summarized diagrammatically as A, B, and C. Numbers refer to objects illustrated in Figure 11 (a). For exercise see text.

A good example of the use of fossils in correlation is provided by the *graptolites*, an ancient group possibly related to primitive chordates,† precursors of the vertebrates (Fig. 12). Being planktonic† organisms, floating in the sea, they were widely distributed geographically, which together with their relatively rapid morphological change through time makes them admirable for correlating rocks of Lower Palaeozoic age.

Appendix 2

Early attempts at dating

The combination of lithostratigraphy and biostratigraphy gives us a relative order of events, and enables such events recorded at individual localities to be fitted together to give the history of a whole region. But this integration does not indicate how many millions of years it took for a certain sequence to be deposited. Without the aid of radiometric dating (Unit 2), it is extremely difficult to say whether events recorded in the geological column were crammed into a period of several hundred thousand years or whether they took place over periods of thousands of millions of years. Prior to the development of radiometric dating, various quantitative techniques for estimating the duration of geological time had been tried.

One method was to determine the amount of sodium added to the oceans every year by rivers (see Unit 24, on geochemical cycle of sodium); if this could be determined, the resultant value could be divided into the total amount of sodium present in the oceans to give the age in years of ocean water. One estimate using this method gave a figure of 90 million years.

This was based on assumptions that the oceans were originally fresh water and that once it entered them the sodium stayed there. Are these assumptions valid?

No, because rocks formed in the oceans contain sodium, and may later form land areas subject to weathering—hence the sodium may be recycled (see Unit 24, p. 10). It is unlikely that the Earth's oceans were ever fresh water.

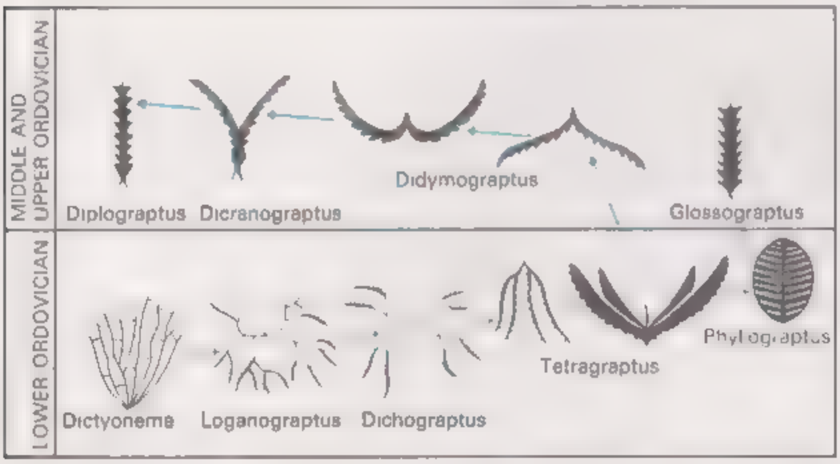


Figure 12 Diagrammatic summary of the main evolutionary changes (of simplification of colony form) occurring in the graptolites during the Lower Palaeozoic (compare the principle with 'evolution' of screws and nails shown by Prof. Pentz in TV 21)

Another method of estimating geological time was to try and find out average rates of deposition, in thickness per year, of modern sediments, and then apply the figure so obtained to sequences of ancient strata. As might be expected, the estimates varied considerably from 3 to 1000 million years! Rates of deposition depend on many factors, among them climate, rates of subsidence of ocean floors or land areas, and reduction of sediment volume by compaction due to pressure of overlying layers.

Answers

1 It is difficult to be precise. The lower sands and gravels must be pre-1920, the upper ones must be post-1920.

2 'Fossil' 1 tells us only that the sediments are pre-1920. But 'fossils' 3 and 6 enable us to be more precise, and put the age of these sands and gravels at pre-1900.

3 Again 'fossil' 7 is of little use in providing an accurate age, since it can tell us only that the peat is post-1900. However, 'fossil' 2 did not come into use till 1920, which means the peat must be at least post-1920. Additional evidence comes from the overlying clays, where 'fossil' 5 has restricted range from 1920–30. That means the underlying peat cannot be younger than 1930; so 1920–30 is the correct answer.

4 From the same reasoning as above, the correct answer must be 1920–30.

---

3 *Radiometric Dating*

Fortunately, radiometric dating of a rock can give an age within certain limits of error. Usually, certain constituent minerals of a rock are separated out and analysed, although it is possible to obtain whole-rock dates by analysing the entire rock. In either case the date obtained is that for an event in the history of that rock. For instance, an igneous rock starts to 'age' when it has cooled past a certain temperature, which will result in the products of radioactive decay being trapped within the rock. For metamorphic rocks, the date recorded will not be that for the original formation of the rock, but that when the rock cooled after it had been recrystallized in the solid state during metamorphism. Dating of sediments can be made on minerals formed during lithification† or diagenesis†, but is usually achieved by considering their relation with associated igneous rocks, and sometimes even metamorphic rocks.

You can read a full account of radiometric dating (as black-page material) in Chapter 2 of *Understanding the Earth*. The principle of radioactive decay has already been discussed in Unit 2.

The method by which 'absolute' ages are given to the divisions of the stratigraphic column is illustrated in Figure 13, in which are given the ages (in millions of years) of a number of igneous rock bodies associated with a sedimentary sequence.

Work out the possible age range for the sedimentary rock units labelled Oligocene, Eocene, Cretaceous and Jurassic.

(The units given as examples are defined below, and in Table 1 on page 17.)

JURASSIC The granite cuts through it so it must be older than 100 Ma. Its maximum age cannot be determined.

CRETACEOUS Deposited on top of granite so it must be younger than 100 Ma but it is overlain by lava flow which is 60 Ma old and this, therefore, must be its minimum age.

EOCENE Sandwiched between two lavas so it must be less than 60 Ma and more than 30 Ma old.

OLIGOCENE Must be less than 30 Ma because it is underlain by a lava of this age, but it is cut by the 20 Ma old dyke* (as is the rest of the sequence), so it must be older than 20 Ma.

From this example we can deduce the following minimum and maximum ages for each unit in the sequence.

	Minimum	*Maximum*
Oligocene	20 Ma	30 Ma
Eocene	30 Ma	60 Ma
Cretaceous	60 Ma	100 Ma
Jurassic	100 Ma	?

To define the ages still further would need more dated samples. This is how the originally qualitative biostratigraphy has become quantitative. As more and more radiometric dates are measured, it will become more and more precise.

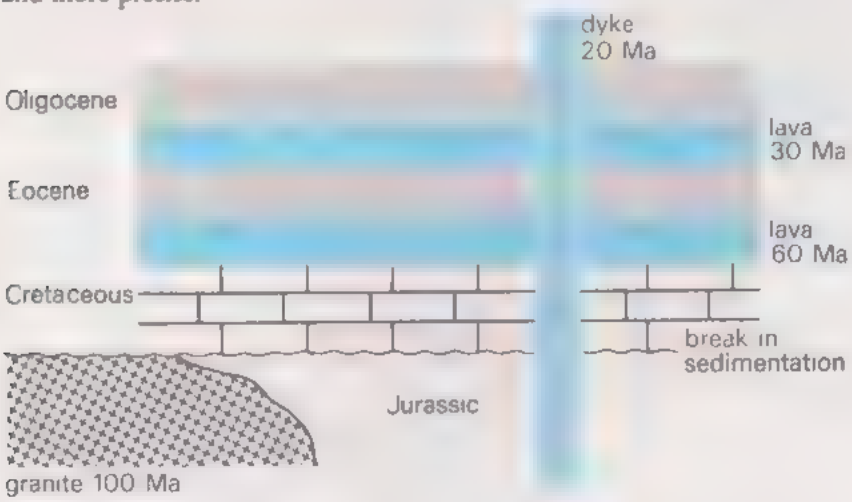


Figure 13 Determining possible age ranges of stratigraphic units; discussion in text.

Stratigraphic terms

On Table I (p. 17) which summarizes stratigraphic terms, you will see a column headed 'Periods and Systems'. At this stage it is difficult to discuss stratigraphic nomenclature fully—indeed it is unnecessary. The main problem you should appreciate is that geologists are attempting to achieve an ideal situation whereby geological time is divided into well-defined segments, say 100 Ma long, which would then be given a specific name. This would be true time-stratigraphy analagous to our method of subdividing historical time into centuries. For geological time, this is still some way off. As you have seen, even with radiometric dating, which is certainly not the ultimate in precision, such a state of affairs is only just beginning to be approached. Therefore the present system is a compromise based largely on fossil evidence, backed up and quantified by radiometric dating.

* *A dyke is a near vertical sheet of igneous rock intruded into pre-existing rocks.*

What is the type of stratigraphy that is based on an examination of the fossil content of rocks?

Stratigraphy based on fossil evidence is called *biostratigraphy*, and approximates to time stratigraphy, as evolution is known to be time-dependent.

Can you remember the other method of dividing up the stratigraphy of a region?

Lithostratigraphy, based purely on the physical characters of rocks, is the least time-dependent type of stratigraphy.

Each of these types of stratigraphy has a hierarchy of divisions, from the very large to the very small. *Do not* attempt to learn the terms in Table I. You will, however, find it useful to remember that the longest intervals of geological time, such as the Palaeozoic and Mesozoic are termed *Eras*, whereas the shorter intervals, for instance the Devonian and Jurassic, are known as *periods* or *systems*.*

eras

periods systems

As you can see from Table I, each system was first defined in a particular country or area and takes its name from it. It is convenient, because it means that there is a common standard sequence of strata to which all workers can refer. This standard is known as a *type section*. For example, the type section of the Ordovician is in North Wales. Although you are not expected to know the stratigraphic table parrot fashion, you may find the information given in Table I concerning stratigraphic terms of some interest. During the Course we often refer to some of these terms, which you can look up on the colour chart in *Understanding the Earth* if you cannot remember their age. You will, with time, assimilate this geological vocabulary as you read through the Course.

type section

[illegible] page 26

(a) (b) (c)

* *There is, by definition, a difference between a period and a system but it need not concern us here.*

Appendix 2

Key Developments in Stratigraphy

100 BC to AD 100	Roman naturalists, such as Lucretius, Strabo and Pliny the Elder recognized the uniformity of nature's processes; a conclusion which only regained general acceptance in the nineteenth century AD.
1508	Leonardo da Vinci recognized fossils as sea shells.
1600	Giordano Bruno burnt in Rome for stating that there had never been a deluge in the Biblical sense, but that the positions of land and sea had changed many times.
1669	Neils Stensen (Steno), a Dane resident in Italy, suggested that stratified rocks were originally deposited as horizontal layers, and that the upper layers were younger than the lower ones (assuming Earth movements had not inverted them).
1760	Arduino recognized the major threefold division of rocks in N. Italy; this pattern was soon accepted in other countries.
1812	Georges Cuvier published an account of the stratigraphy of the Paris Basin based on the sequence of invertebrate and vertebrate fossils. His work was similar to that of William Smith whose ideas had already gained favour at this time, even though his map (see below) was published three years later. In his account, Cuvier demonstrated successive extinctions of faunas, but accounted for them by a series of catastrophes.
1815	William Smith (the Father of English Geology) published the first geological map of England and Wales in which he showed, for the first time, that strata could be recognized by the fossils which they contained; and by doing so he showed that rock sequences could be correlated by the fossils they contained.
1859	Publication of Charles Darwin's *The Origin of Species*, in which evidence was marshalled against the catastrophist school of thought and new species were shown to be the result of evolutionary changes through time.

From this period on, not only was palaeontological correlation possible, but a relative order of strata could be worked out for any region by comparative studies of the fossils contained in its rocks.

1896	Becquerel discovered radioactivity, which led seventeen years later to the publication by Arthur Holmes of the first paper on radioactive dating of rocks. This has led to the development of a quantitative *geologic time-scale*.
1960	Publication, by Holmes and others, of a radiometric time-scale in which eras and periods were given quantitative age parameters.

Appendix 3

The Coastal Environment

This Unit's TV programme examines a small area of the north Norfolk coast near Hunstanton (which is just off the west side of Fig. 14 (a)), and gives some examples of how the present gives the key to the past. In the programme there is insufficient time to develop a geological model of this environment—a model which summarizes the rock record that is produced.

environment model

The key to understanding how a vertical sequence of rocks may be built up in a coastal environment is the traverse marked on Figure 14 (a), and shown in section in Figure 14 (c). The characters of these sediments are summarized on Plate A, facing p. 48, and in Figures 14 and 15.

What do you notice about the sequence (or, if you like, order) of different sediment types *across* the coastal area, and *down* the borehole?

They are the same: turn the borehole sequence on its side! But the sediments at the base of the borehole are *older* than those now forming on the beach (remember the law of superposition) and are now lower than the comparable sediments forming just below sea-level at the present time.

What does this suggest?

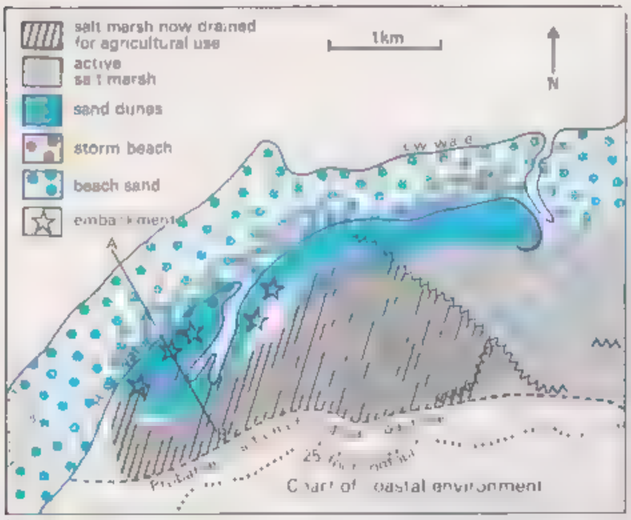
The simplest explanation is that the area has been slowly sinking—or the sea slowly rising,* and that deposition of new sediments has kept pace with this relative sea-level rise. Thus the accumulation of layer upon layer of sediments (vertical sedimentation) has been accompanied by the building out of the coastline (lateral sedimentation, as illustrated in Fig. 15). This theory is borne out by the existence of an old coastline well back from the present one (see Fig. 14).

So in the case of this coastal environment, the lateral sequence of sediments forming at the present day is repeated vertically through the older sediments, as seen in the borehole. In ancient sediments it is easier to see vertical rock sequences (of a few metres), rather than lateral ones (of a few kilometres), as exposures of rocks are often limited, being covered by soil and vegetation. So, for ancient rocks, this 'rule' can be reversed to interpret what the ancient environment might have been like. For instance, if the borehole sequence shown in Figure 14 (e) was obtained by drilling through rocks, say, of Cretaceous age, we could construct a model for the environment along the lines already described. With more boreholes (or surface exposures) it would be possible to fill in more details, such as the trend of the coastline, and even tidal current directions. This type of interpretation is discussed for another type of environment on pp. 185–90 of *Understanding the Earth* (to which you are referred in the main text of this Unit).

Figure 14 (opposite) Summary of the coastal environment at Holme next the Sea, near Hunstanton, north Norfolk.
(a) Sketch map of the coastal area just east of Hunstanton, north Norfolk.
(b) Aerial photo of the area, with the other (west) side of the Wash in the far distance.
(c) Section along traverse A–B marked in Figure (a).
(d) Geological model of the area, key as in Figure (a).
(e) Rock section obtained in borehole sunk at locality marked on Figure (d)
(f) Sketches of organisms and burrows found in this Coastal environment.
(i) Lugworm, Arenicola marina
(ii) Razor shell (Ensis), *showing burrowing action*
(iii) Cardium edule *(bivalve) in its burrow*
(iv) Macoma *(bivalve) in its burrow*
(v) Crab in burrow
(vi) Corophium, *its burrows are U-shaped (see TV 26)*

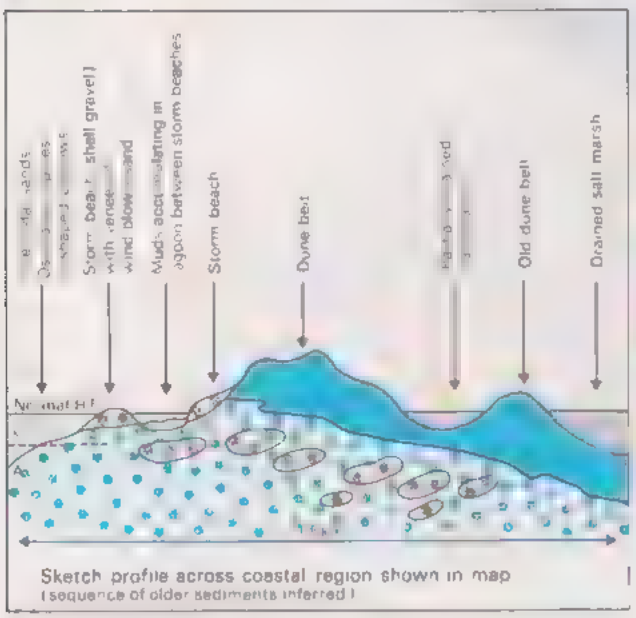
* *Probably both—sea-level being raised by the melting of polar ice-caps at the end of the last ice age.*

Chart of coastal environment

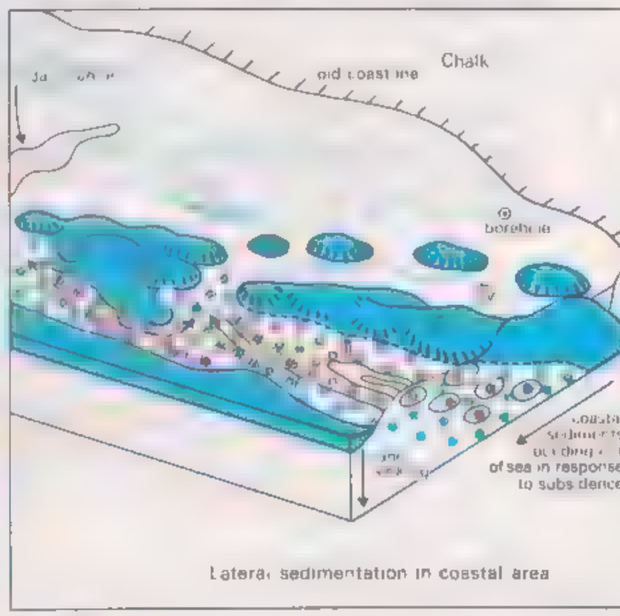


(a)

(b)



(c)

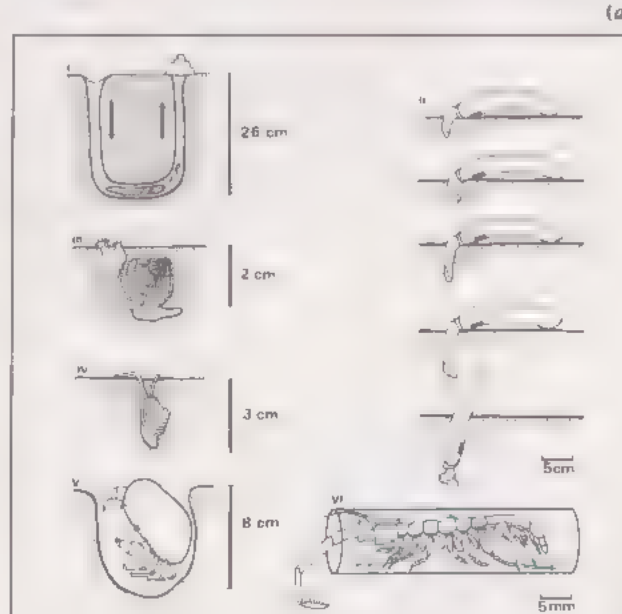


(d)

Sequence in borehole

Lithology	Fossils
Black muds and silts	Small U burrows and small burrowing bivalves in place not beds
Well sorted medium sands with dune bedding	None or few fragments of shells
Cross bedded coarse sands and gravels with numerous shells	Numerous shells often broken and disarticulated mixture of bottom dwelling anchored types, shallow and deep burrowers and borers
Flat bedded moderately sorted medium sands	U burrows and burrowing bivalves (large) in place

(e)



(f)

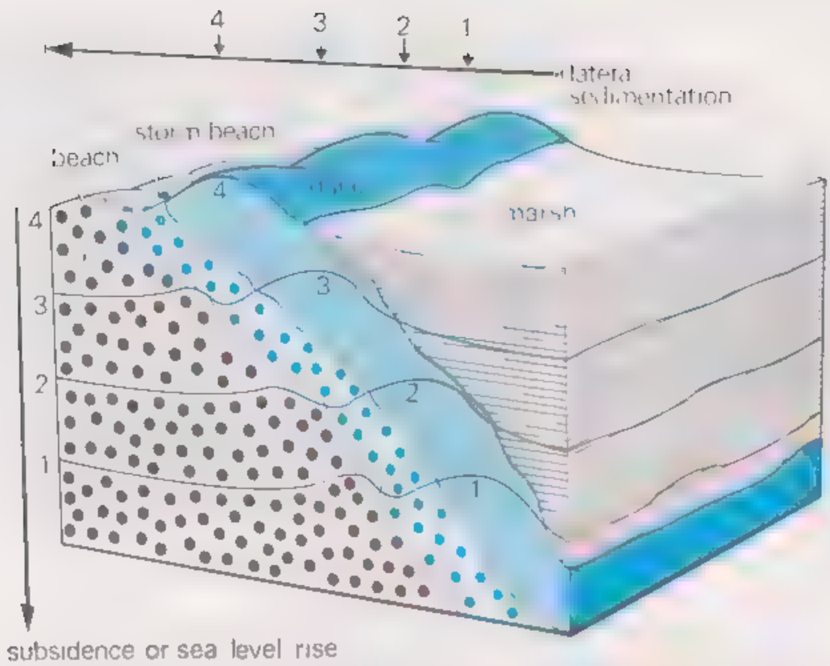


Figure 15 Sketch to show how belts of different sediments may migrate due to lateral sedimentation. Numbers 1, 2, 3 etc. represent successively later positions of the dunes through time.

From GeoTimes, *May–June* 1959, *Vol. III, No.* 8

Dating of Mining Camps with Tin Cans and Bottles

by CHAS. B. HUNT *

Old mining camps, ghost towns, in fact most abandoned habitations, arouse general curiosity and interest. People visiting such abandoned places soon begin poking around for relics and enjoy imagining the way life once went on there. Part of the fun is guessing when a place was occupied, when it was abandoned and why. This can have practical applications too, such as in the study of a mining district to learn whether the periods of activity correlate with the swings in the economic cycle or with the type and grade of ore being mined or prospected.

A favorite means of arriving at the dates is to uncover the layers of old newspapers or magazines that frequently were used to help insulate log cabins and other frame buildings. But approximate dates also can be obtained by observing the litter in the camp dump, more respectfully known by archeologists as the midden. The design or style of most commonplace articles and methods of manufacturing them have evolved greatly in the past hundred years so that such articles as tin cans and bottles can be useful for dating.

In the western United States most of the mining camps and ghost towns are less than 100 years old, and four ages of habitations can readily be distinguished by observing the accumulated litter. The oldest camps, those active before about 1900, are characterized by soldered tin cans, by beer bottles with hand-finished necks made for cork stoppers, and by square nails.

Mining camps of the period from 1900 to World War I are characterized by round nails and by bottles with hand-finished necks, but by this time the beer and soft drink bottles were being made to accommodate metal caps instead of cork stoppers. Soldered tin cans continued in use throughout this second period.

The third period includes the 20's and early 30's. At camps of this period the bottles have machine-finished necks and the tin cans are crimped instead of being soldered, and these artifacts are associated with miscellaneous car parts including that familiar Ford monkey wrench known as 'the knuckle breaker'.

The latest period, the last 20 years, has been the era of the beer can associated with aluminium cooking utensils.

Tin cans and bottles are so uniform and commonplace today it is difficult to realize that only half a century ago the methods of manufacturing both were primitive. Figure 1 illustrates the contrast between the old type soldered tin can and the modern type having crimped ends which was manufactured after World War I. In the eleventh edition of the Encyclopedia Britanica (v. 26, p. 1000), published before the new manufacturing method was adopted, we learn that in Great Britain tin cans for preserving foods began to be manufactured in quantity about 1834, and that large quantities were shipped to the United States until about 1890, when domestic production began expanding greatly. The old method for manufacturing 'tinned cans' is described as follows (v. 10, p. 613):

'The canister, which has been made either by the use of solder or by folding machinery only, is packed with the material to be preserved . . . the lid is secured by soldering or folding. Sterilization is effected by

* *Geologist, U.S. Geological Survey, Denver, Colo.; former Executive Director, American Geological Institute.*

placing the tins in pressure chambers, which are heated by steam to 120° C or more. . . . Sometimes a small aperture is pierced through the lid, to allow the escape of the expanding air, such holes before cooling closed by means of a drop of solder. This process . . . is employed on an enormous scale, especially in America.'

The old type tin can was not altogether satisfactory for the account goes on to state that there was a distinct limit to the length of period of preservation of canned food, and that the use of tin plate for preserving acid substances like tomatoes and peaches was highly objectionable.

About the time of World War I, however, methods of manufacturing tin plate and methods of sterilizing foods in cans were greatly improved, and these changes in manufacturing methods are recorded in mining camps by the appearance of tin cans having crimped ends and no soldering (Fig. 1).

Finally, during the 30's the modern beer can arrived with its characteristic triangular openings and brightly colored printing.

The manufacture of glass is one of the oldest industries, dating back several thousand years before the Christian Era, and may have begun by fusing sand and soda in an open fire. Not until the beginning of the Christian Era, when the blowpipe was invented, were means found for producing clear, or crystal glass (Phillips, 1941, p. 7). By the end of the third century window glass was being made (Phillips, 1941, p. 8). In this country glass manufacture is believed to have been the first industrial enterprise undertaken in the colonies. A factory making bottles and glass beads for trading with the Indians was established at Jamestown in 1607 or 1608 (Phillips, 1941, p. 16; Silverman, 1954, p. 143). But as late as 1900 the methods of manufacturing glass were not basically different from the methods that had been used during the preceding 1500 years (Phillips, 1941, p. 19).

One of the most easily recognized changes in bottle styles occurred about the time of World War I, along with the change in method of manufacturing cans. Before that time the necks of bottles were finished by hand; after that time they were finished by machine (Fig. 2). In the modern machine-finished bottle, the seams from the mold extend the whole length of two sides and even across the lip of the neck. Prior to World War I the necks were finished by hand, and the seams on bottles made during earlier periods end at the base of the neck which is a layer of glass wound around the partly finished bottle. The hand process of bottle manufacture has been described as follows (Powell and Rosenhain, 1910, p. 95; see also Thorpe, 1912, p. 730):

'A bottle gang . . . consists of five persons. The "gatherer" gathers the glass from the tank furnace on the end of the blowing-iron, rolls it on a slab of iron or stone, slightly expands the glass by blowing, and hands the blowing iron and glass to the "blower". The blower places the glass in the mould, closes the mould by pressing a lever with his foot, and . . . blows down the blowing iron. . . . When the air has forced the glass to take the form of the mould, the mould is opened and the blower gives the blowing iron with the bottle attached to it to the "wetter off". The wetter off touches the top of the neck of the bottle with a moistened piece of iron and by tapping the blowing iron detaches the bottle and drops it into a wooden trough. He then grips the body of the bottle with a four-pronged clip, . . . and passes it to the "bottle maker". The bottle maker heats the fractured neck of the bottle, binds a band of molten glass round the end of it and . . . shapes the inside and outside of the neck. . . . The finished bottle is taken by the "taker in" to the annealing furnace. . . .

Figure 1 Old type tin can (above) and modern type with crimped seam and ends.

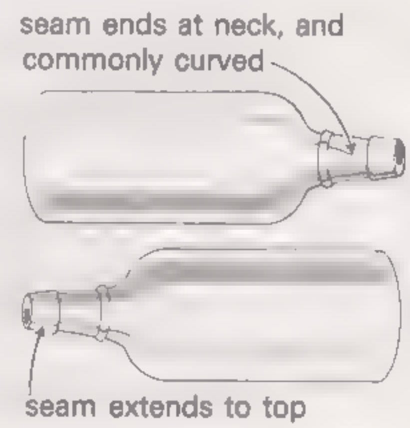


Figure 2 Old type bottles with hand-finished necks (top) have mold seams ending at the neck, commonly in a curve On machine-finished bottles (bottom) the seam extends to the top

'The processes of manipulation which have been described, although in practice they are very rapidly performed, are destined to be replaced by the automatic working of a machine.'

The change to machine methods had been anticipated by the invention of the Owens bottle machine about 1900 (Silverman, 1926, p. 897), and machine-made bottles began reaching mining camps in quantity after World War I.

An earlier change in bottle style occurred about 1900. During the nineties and earlier, beer and soft-drink bottles were made to receive cork stoppers, but after 1900 they were made to receive metal caps (Fig. 3).

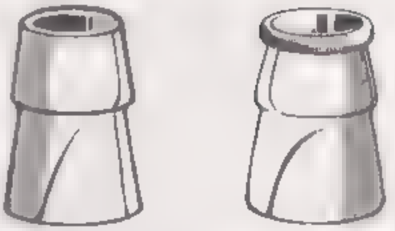


Figure 3 Neck of pre-1900 beer bottle, made for cork stopper (left); after 1900 beer bottles and soft drink bottles were made for metal caps (right). Both these necks were hand finished.

The color of glass fragments scattered about abandoned mining camps can also be helpful in determining the period of occupancy. Camps active before World War I are characterized by abundant purple fragments whereas camps younger than World War I generally have little purple glass, and a high percentage of clear glass. The purple glass at old mine camps originally was clear, but exposure to sunlight causes photochemical changes in the manganese oxide in the glass and these changes cause the purple coloring (Alway and Gortner, 1907, pp. 4–7; Gortner, 1908, pp. 157–162; Lucas, 1922–23, pp. 72–3; Hoffman, 1937, pp. 229, 3649). When glass manufacture was largely by hand the manufacturer could adapt the process to the material at hand, but when the methods became mechanized the materials had to be adapted to the process, and less variation in composition could be allowed. Since the advent of machine-made bottles, about the time of World War I, the materials used in making glass have contained fewer impurities that would change the color of the glass.

That the purple color in old glass is due to manganese oxide in the glass has been shown by numerous chemical analyses (see for example Alway and Gortner, 1907; Gortner, 1908; Lucas, 1922–23; Hoffman, 1937). Invariably purple glass contains high percentages of manganese—more than 0.1 per cent and in some examples as much as 1.0 per cent. The intensity of the color is correlative with the manganese content.

That the purple color also is due to exposure has been demonstrated by a number of experiments in which some glass was partly covered with paint and exposed to sunlight. When the paint was removed the exposed part was colored whereas the protected part was not (Rosenthal, 1917, p. 734). One can satisfy himself that this is so by finding glassware partly buried in the ground; the part that was buried remains clear while the part that was exposed has become purple (Simpson, 1905, p. 236; Alway and Gortner, 1907, pp. 5, 6) (Fig. 4). The color change is by no means peculiar to deserts and high altitudes; it occurs also in tropical and temperate regions and at low altitudes (Rueger, 1905, p. 1206; Crookes, 1905, p. 73).

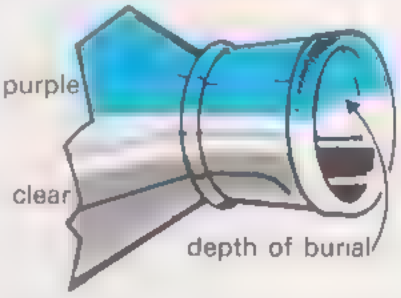


Figure 4 Rim of old jar with hand-finished neck that was partly buried and partly exposed. The exposed part is purple; the buried part remained clear.

The length of time required for glass to become purple depends partly on the composition of the glass, especially its manganese content, partly on the exposure to sunlight, and partly on the color of the background. Given optimum conditions the color change can occur in less than a month (Gortner, 1908, p. 162). Exposure of less than a year produced violet color in most old glass containing appreciable quantities of manganese, and in some bottles the coloring occurred before the gummed paper labels were destroyed (Alway and Gortner, 1907, p. 5). The color becomes more pronounced as the time of exposure is lengthened. Background colors seem to affect the rate of color change too. Violet colored backgrounds accelerate the color change, presumably by favoring the ultra-violet rays; black and brown backgrounds seem to retard the change. Backgrounds of white, yellow, blue, and red seem to have no influence. Backgrounds containing manganese have no effect (Gortner, 1908, p. 162).

Few modern bottles made of clear glass become purple. This is because their manganese content generally is low, not because the time of exposure

has been insufficient. Modern clear glass like liquor bottles or grocery bottles is likely to contain less than 0.001 per cent manganese and only 0.02 per cent iron. Despite the fact that some old-style bottles contain little manganese and are clear, an abundance of purple glass at a mining camp nevertheless suggests a pre-World War I date because so much of the utility glass of that era contains enough manganese to produce the color.

Bottle glass at old mine camps also is likely to have its surface corroded; some surfaces are beautifully iridescent. This property of old utility glass resulted from excessive alkalis, especially sodium (Morey, 1925, p. 392), in the mix. Most of the utility glassware at old mine camps is known as soda-lime glass and is a mixture of soda, lime, and silica (Morey, 1933, p. 742). Pure silica would be the most desirable material for most glass except the cost of manufacture is prohibitive because both the melting point and viscosity are high; other oxides, alkalis, are added to lower the melting point and viscosity (Morey, 1933, p. 743). Fluxes like sodium carbonate and sodium sulfate (Finn, 1938, p. 891) supply the alkalis that make melting easier but sodium especially makes the glass more susceptible to corrosion (Morey, 1925, p. 392). The alkali content in glass was not well controlled until machine methods were adopted, and glass at old camps is likely to have corroded and iridescent surfaces.

The history of changing styles in tin cans and bottles has an interest all its own, for those who would pursue the subject more deeply, a bibliography is added.

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Self-Assessment Questions

Question 1 (*Objective 1*)

Match the terms in the first list with the definitions given in the second list by placing the appropriate letters alongside the terms.

1 Uniformitarianism
2 Energy of environment
3 Porosity
4 Permeability
5 Greywacke
6 Arkose
7 Cross stratification
8 Andesite
9 Granite

A The ratio of volume of voids to particles in a rock.
B Inclined layering in sedimentary rocks produced by current action.
C Poorly sorted sediment, derived from andesites and metamorphosed and deformed sediments.
D The present is the key to the past.
E Extrusive volcanic rock abundant in young mountain chains.
F A measure of the ability of fluids to flow through rocks.
G A sedimentary rock with a mineralogical composition similar to that of granite.
H The degree of turbulence and current velocity in a sedimentary environment.
I Coarse-grained intrusive igneous rock composed mainly of quartz and feldspar.

Question 2 (*Objective 1*)

Match terms in the first list with the definitions or words given in the second by placing the appropriate letters alongside the terms.

1 Lithostratigraphy
2 Biostratigraphy
3 Law of superposition
4 Law of faunal succession
5 Era
6 Period

A Mesozoic.
B Correlation of rock units based on their physical characters.
C Devonian.
D In a sequence of rocks, the highest units are the youngest, provided the sequence has not been inverted by Earth movements.
E Correlation of rock units based on their fossil contents.
F Changing assemblages of fossils through a rock-sequence, being caused by evolutionary changes in the original faunas, reflect a time sequence.

Question 3 (*Objective 2*)

What is the basic assumption underlying the statement that 'the present is the key to the past'? Write a short sentence describing it.

Question 4 (*Objective 3*)

List the five major features you would investigate when studying a modern sedimentary environment.

Question 5 (*Objective 4*)

Which of the features that you listed in Question 4 is likely to 'survive' in the geological record?

Question 6 (*Objective 5*)

You are examining the rock obtained from a borehole, and find the following sequence of lithologies, from the top down.

7 Black finely-bedded clays, with small tubular burrows, bivalve fossils with the shells closed, and abundant plant remains.

6 Very well-sorted sandstones (0.2 mm), showing large-scale cross-bedding.

5 Poorly-sorted coarse sandstones and conglomerates, with a variety of fossils including broken shells.

4 Well-sorted sands (0.2 mm), with flat bedding, and 'U'-shaped burrows.

3 Poorly-sorted coarse sandstones and conglomerates, with a variety of fossils, including broken shells.

2 Very well-sorted sandstones (0.2 mm), showing large-scale cross-bedding.

1 Black finely-bedded clays, with small burrows, and bivalve fossils with closed shells, and abundant plant remains.

(a) Select from the following—salt marsh, sand dunes, storm beach, intertidal sands—the appropriate depositional environment for each of the units 1–7 above.

(b) During deposition of units 1–4, was the sea advancing or retreating? During deposition of units 5–7, was the sea advancing or retreating?

Question 7 (*Objective 6*)

Given below are definitions (A–F) of various structures within a delta; select from the second list (1–6) the most appropriate term to place alongside each definition.

A The material laid down in horizontal layers on top of a delta.

B A river branch flowing away from the main stream and not rejoining it.

C The series of inclined layers accumulated by lateral sedimentation on the delta.

D Part of a delta complex formed during deposition from a single distributary.

E The layer of finer material carried out and deposited in the open sea away from the delta.

F Areas of vegetation covering flat-lying ground.

1 Intertidal swamp; 2 Bottom-set beds; 3 Distributary; 4 Fore-set beds; 5 Sub delta; 6 Top-set beds.

Question 8 (*Objective 6*)

Match the types of sediments given in the first list (A–D) to the environment (1–4) where they are most likely to occur, by inserting the appropriate letter alongside each environment.

(A) clays; (B) silty clays; (C) silts and sands; (D) laminated clays and silts with abundant roots.

(1) Inter-distributary swamps (2) bottom-set beds (3) fore-set beds (4) top-set beds

Question 9 (*Objective 6*)

Given below is a list of sedimentary rocks which formed in a deltaic environment. Arrange these in the order in which you might expect to find them along a traverse from land to sea.

Insert numbers 1–7

A Silts and shales

B Coal

C Limestone

D Shale

E Sandstone with large-scale cross-bedding

F Seat earth

G Sandstones with small-scale cross-bedding

Question 10 (*Objective 6*)

If a deltaic sequence (of the kind you considered in Question 9) started with limestone at the base, and finished with coal, it would have been deposited in an environment in which the shoreline of the delta was retreating landwards. *True or False?*

Question 11 (*Objective 7*)

Indicate which of the following plate margin types is the site of orogenesis by placing a tick alongside the appropriate type.

1 Constructive margins; 2 Destructive margins where continent meets continent; 3 Conservative margin; 4 Destructive margin where oceanic plate meets continental plate.

Question 12 (*Objective 8*)

Fold mountains are produced by the following (indicate whether true or false):

		True	*False*
A	By compressional forces in the Earth's crust.		
B	By the intrusion of large bodies of granite and andesite.		
C	By the collision of adjacent continental lithospheric plates.		
D	By the underriding of oceanic plates beneath continental plates.		
E	By isostatic adjustment of the crust.		
F	By phase changes in the mantle.		

Question 13 (*Objective 9*)

Ancient orogenic belts are considered to be 'fossil' destructive margins because (indicate whether true or false):

		True	*False*
A	Their contained sedimentary rocks resemble those being formed around present-day destructive plate margins.		
B	They contain thick sequences of basaltic rocks similar to those found along present-day oceanic ridges.		
C	Their tectonic structures are comparable to those found in young fold mountain areas.		
D	They contain intrusive igneous rocks comparable to those forming in present-day fold mountain belts.		
E	They contain large faults comparable to transform faults along present-day plate margins.		

Self-Assessment Answers and Comments

Question 1

You should have matched the following:

1 D; 2 H; 3 A; 4 F; 5 C; 6 G; 7 B; 8 E; 9 I.

Question 2

You should have matched:

1 B; 2 E; 3 D; 4 F; 5 A; 6 C.

Question 3

The assumption underlying the principle that the present is the key to the past is that physical and chemical 'laws' applied as much in the past as they do today, although the relative importance of various natural processes may have changed through time.

Question 4

You should have listed: (1) topography; (2) climate; (3) water conditions; (4) flora and fauna; and (5) sediments.

Question 5

Sediments and their contained fossils would survive in the geological record.

Question 6

(a)

salt marsh	1 and 7
sand dunes	2 and 6
storm beach	3 and 5
intertidal sands	4

(b) The sea was *advancing* inland between Units 1 and 4, after which it retreated. The model described in Appendix 3 shows the case where the sea is *retreating*, due to a net gain of sediment into the area.

Question 7

You should have matched:

1: F, 2: E, 3: B, 4: C, 5: D, 6: A.

Question 8

You should have matched:

A: 2, B: 3, C: 4, D: 1.

Question 9

The order, from top down, is:

B
F
E
G (see Figure 13.31 of *Understanding the Earth*)
A
D
C

Question 10

False: it would be deposited by a delta advancing *into* the sea by lateral sedimentation, so that shallower sediments come to lie on deeper water types.

Question 11

You should have ticked 2 and 4; both these margin types suffer orogenesis. Constructive margins (1) are oceanic ridges—submarine mountain ranges which are *not* produced by orogenesis.

Along conservative plate margins (3), plates slip past one another accompanied by relatively little deformation.

Question 12

A, C and D are true. The remainder are not true. B is only part of the process of orogeny, not a cause. E occurs after orogenesis and may be produced by F.

Question 13

A, C and D are true; B and E are characteristic of constructive plate margins, which do not occur within orogenic belts.

Acknowledgements

Grateful acknowledgement is made to the following sources for illustrations used in this unit:

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Notes

Plate A—an Explanation

The photographs illustrate a traverse across the coastal area illustrated in Figure 14, starting at near the low tide mark and working inland.

1 Mussel bank; the mussels trap finer sediment during their feeding activities, and also help to protect the sediment against current activity. Mussel banks are not shown on the TV programme, or on Figure 14; they occur at low tide just to the west of the study area, they may be attached to hard rocks, or sediments, as shown here.

2 Symmetric ripple marks formed by oscillatory movements of shallow water under wave action (see p. 182 of *Understanding the Earth*). In the TV programme, the formation of *asymmetric* ripple marks is described.

3 Symmetric ripple marks which have flat tops due to erosion after their formation. The photo was taken as the tide covered them once more.

4 Surface expression of lug worm burrows; the depressions mark the inlet side of the burrow, the 'wormcasts' the exhalent side (see Fig. 14 (f)).

5 Storm beach (or berm) gravels containing pebbles, coarse sand and shells. The penny (old!) rests against an oyster shell (fixed habit), below that is a scallop, to the left a mussel (fixed, anchored by 'fibres'), and the shells adjacent to the scallop (to the right, and below) bored into the nearby chalk.

6 Sand dune belt with storm beach beyond enclosing muddy area just covered by sea water. This view is looking east along the coast.

7 Salt marsh vegetation. Samphire grass (*Salicornia*) growing in fine muds. Small water filled channels which fill with each tide may also be seen.

8 Salt marsh sediments the top of which is covered in a thin 'mat' of algae filaments which help to stabilize the sediment. The excavation shows the layering of the sediment brought out by black and orange colouration (due to iron sulphide (FeS_2) and its oxidation products respectively).

9 Aerial view of coast about 8 km to east of study area, showing part of a linear sand bank (or sandspit) with poorly developed dunes, and backed by saltmarsh showing characteristic tidal channel pattern.

PLATE A


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